A Novel Signal Processing-Based Approach for Accurate and Fast Islanding Detection

BY

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عمادة الدراسات العليا
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To the Spirit of my Father

ACKNOWLEDGMENTS

Foremost, I would like to express my sincere gratitude to my supervisor for his continuous support, encouragement and inspiring guidance throughout my thesis .

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Last but not the least, I would like to thank my family especially my parents for their continuous and endless support throughout all my life.

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Nomenclature

DG	Distribution Generator
NDZ	Non-Detection Zones
CT	Current Transformer
PT	Power Transformer
CSA	Canadian Standard Association
PLCC	Power Line Carrier Communication
DLC	Distribution Line Carrier
SCADA	Supervisory Control And Data Acquisition
OVP	Over Voltage Protection
UVP	Under Voltage Protection
OFP	Over frequency Protection
UFP	Under frequency Protection
WT	Wavelet Transform
DFT	Discreet Fourier Transform
CFT	Continuous Fourier Transform
STFT	Short Time Fourier Transform
HHT	Hilbert Huang Transform
IMF	Intrinsic Mode Function
PV	PhotoVoltaic
IG	Induction Generator

PCS	Power Conditioning Systems
ANN	Artificial Neural Network
PNN	Probabilistic Neural Network
ANFIS	Adaptive Neuro Fuzzy Inference System
RF	Random Forest
SVM	Support Vector Machine
FFT	Fast Fourier Transform
DFIG	Double Fed Induction Generator
DT	Decision Tree
AIS	Artificial Immune System
DSP	Digital Signal Processing
PCA	Principle Component Analysis
SVD	Singular Value Analysis
NNT	Neural Network
BP	Backward Propagation
MSE	Mean Square Error
PWM	Pulse Width Modulation
SVS	singular Value Spectrum
MLP	multi-layer perceptron

THESIS ABSTRACT

NAME: Mu'Taz Ibrahim Jawadeh

TITLE OF STUDY: A Novel Signal Processing-Based Approach for Accurate and Fast Islanding Detection

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With recent increases in the contribution of dispersed or distributed energy resources to electric power production, the subsequent effects on power systems are becoming increasingly important. As an example, a critical situation may arise if protective relays trip a large part of the dispersed generation due to under-voltage in the event of a short-circuit. On the other hand, it is crucial that the protection system acts correctly to protect life and property in other situations. These qualities are referred to as security and dependability. One of the major problems associated with distribution generation is islanding. There are a number of different types of anti-islanding, or loss-of-mains protection, with some implemented in practice and others still in the research stage. This work proposes a new signal processing-based islanding detection technique for distribution generators (DGs).

In the proposed method, the voltage will be measured and then processed using the singular value decomposition theorem (SVD) to extract the principle components of the voltage signal. The principle components contain a representation of the voltage waveform on an n-dimensional space. The effect of islanding on these components is monitored through an artificial neural network (ANN) to diagnose the islanding conditions. Usually, signal processing-based islanding detection techniques are considered fast and accurate. In this technique, islanding is detected faster than most signal processing-based islanding detection techniques. Also, this technique works for distribution resources with different topologies, such as hybrid systems, inverter-based wind turbines, and induction generator wind turbines, unlike other techniques in which a single type of DG is used. The method of robustness was examined in different scenarios, which are systems with variable load changes, the activation of large motors and generators, the switching of capacitor banks, and noisy conditions. Tests under these scenarios proved the effectiveness and robustness of the proposed technique. Throughout this research, SVD is used to detect islanding within the first cycle and this is a major advantage of this technique.

ملخص الرسالة

الاسم الكامل: معتز ابراهيم محمد جواعدة

عنوان الرسالة: طريقة جديدة باستخدام معالجة الإشارة للكاشف عن الجزيرة الكهربائية بدقة وسرعة

التخصص: هندسة كهربائية

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لقد ساهمت مصادر الطاقة الموزعة في زيادة انتاج الطاقة الكهربائية, وتاثيرها على نظام الطاقة اصبح ذو اهمية كبيرة. وكمثال على ذلك يمكن أن ينشأ وضع حرج إذا قمنا بفصل هذا الجزء الكبير من الإنتاج لأي سبب من الأسباب كنقص الجهد او في حالة تماس كهربائي. من ناحية أخرى , ومن الأهمية بمكان أن يعمل نظام الحماية بشكل صحيح لحماية االموال والممتلكات. ويشار الى هذا النظام باسم الامن والإعتمادية

.وهناك عدد من الطرق المختلفة لمكافحة الجزر الكهربائية غير المكتشفة. أو الحماية ضد خسارة التيار الكهربائي. يتم تنفيذ بعضها عمليا في حين لايزال البعض الأخر على المستوى البحثي. في هذا العمل, سنقوم باقتراح تقنية للكشف عن الجزر الكهربائية في مولدات التوزيع. في هذه الطريقة المقترحة سيتم قياس الجهد في الشبكة ومن ثم معالجتها بوسطة تحيليل القيمة غير المتناظرة ومن ثم استخراج ميزات تمثيلية من الجهد باستخدام الطريقة المذكورة ومن ثم معالجتها من خلال الشبكة العصبية الإصطناعية لتشخيص ظروف الجزر الكهربائية. وخلال هذه الدراسة , تم الكشف عن حالة الجزر الكهربائية لنظام هجين ولتربينات رياح مع طبولجيا مختلفة .كنا قادرين على كشف الجزر الكهربائية في اول موجة واحدة من الجهد بعد الفصل

CHAPTER 1

INTRODUCTION

1.1 Motivation

The core of this thesis is to provide a novel method for the detection of islanding conditions, which is required in order to protect the distribution generator (DG) systems that have been implemented in power distribution grids rated 25 kV or less. Recently, new challenges have arisen due to the increased implementation of DGs into distribution busses near electric power consumers. As a result, the traditional protection schemes are in need of development in order to deal with these new circumstances. Hence, traditional protection topologies (e.g., out-of-step monitoring, re-closures, and impedance relay protection zones) need to be improved in order to overcome new protection difficulties, such as the detection of sudden islanding of DG systems. The islanding condition occurs when the DG system is disconnected from the core grid system. Islanding may cause possible damage to the equipment of the power system, in addition to reliability issues and power quality degradation.

Existing islanding detection methods predict islanding by taking into account voltage or frequency deviations (over/under voltage and frequency) both passively and actively. Each method has a pre-sighted sensitivity and a non-sensitive operation condition with variable grades of power quality degradation, which is called the non-detection zone (NDZ). The islanding detection scheme proposed in this thesis takes the detailed theoretical concept of signal decomposition and extends it to include a principle components analysis, thereby exploiting the change which islanding has on the relative variances of the principle components to investigate the state of the system. This paper explores a variety of applications in which the islanding detection scheme is used to improve the common islanding detection methods, where a general form of the method allows the protection engineer to recognize when this scheme can be implemented most effectively.

The practical implementation of this islanding detection scheme comes without significant modifications and capital costs, as it can be implemented by using the existing Voltage Transformers (VT), Current Transformer (CT) and Power transformer (PT) to achieve accurate measurements, in addition to the use of software in the digital relays or low voltage inverters. To start, a brief introduction to the islanding technique and the motivation for the use of distributed generation is introduced. The following chapters will contain the background and the attributes of this technique.

1.2 Types of Distributed Generation

DGs are usually classified based on the type of generator used in its configuration. There are three main types of generator: induction, synchronous, and inverter-based generators. Induction generators are combined with excitation to provide the necessary active power and startup, such as an induction motor. Induction generators are less expensive than synchronous machines, but with a lesser power rating that is usually less than 500 kVA. They are commonly used in wind power production units. Alternatively, synchronous generators require a direct current excitation system, which also needs synchronization with the utility before a connection is required. Synchronous machines are usually implemented with internal combustion machines, gas turbines, and small hydro dams. Also, inverter-based generators are transistor switch based systems. Inverters are usually used in photovoltaic, micro turbines, and fuel cells. A comparison of the various types of distribution generation systems is shown in detail in 1.1 [1].

1.3 Technical Challenges Facing Distributed Generation

There are many existing problems concerning distributed generation. Also, the integration process of DG, with its distributed system, comes with grave challenges, but the major challenge is the ability of the electrical system to cope with consumer side generation. Moreover, the original design of the electrical system

Table 1.1: Types of DG and Typical Capacity [2].

DG	**Capacity**	**Interface with Utility**
Photo-voltaic Cells	30 W to 100kW	Inverter
Wind turbines	200 kW to 3 MW	Synchronous and/or Induction machines, Inverters
Geothermal	3 to 100 MW	Synchronous Generator
Micro Hydro	25 kW to 1 MW	Induction or Synchronous machines
Small Hydro	1 to 100 MW	Induction or Synchronous machines
Combustion turbines	1 to 250 MW	Turbine Synchronous Generator
Combined Cycle turbine	35 to 400 MW	Synchronous Generator
Micro turbines	35 kW to 1 MW	Inverter
Fuel Cells	1 kW to several MVA	Inverter

is a large generator that is situated far away from the distribution side. DGs are smaller generation units, which are connected to a local and low voltage, consumer side, electrical distributed system, as shown in the previous section in 1.1 .The addition of DGs to the current electric power distribution system may cause a reduction in safety, system stability, and power quality. More specifically, in studies [3–9] the technical challenges facing the DG have been reviewed and are summarized by the following points:

1. Voltage Regulation and Losses.

2. The flicker of voltage.

3. DG Shaft Over-Torque During Faults.

4. Harmonic Control and Harmonic Injection.

5. Fault severity short circuit with high levels.

6. Grounding and Transformer Interface.

7. Transient stability.

8. The sensitivity of the protection methods.

9. Coordination between Generators.

10. High penetration impacts on the distribution system.

11. Islanding Control.

Depending on the number of the DGs connected to the grid and the size of the power system, the issues listed above could cause severe problems.

1.4 Background

Islanding is a state in which the distribution generators (DGs) become electrically isolated from the electrical grid connected to it, yet they continue to energize local loads. According to the IEEE929-2000 standard [10]all DGs must be disconnected when an islanding condition occurs. In addition, a 2-second maximum delay is allowed to detect the islanded DGs, according to IEEE 1574-2003 standard [11].

The term non-detection zone (NDZ) is a key feature in understanding the islanding condition, which is a phenomenon that refers to a range of power differences between the power supplied by the DGs and the power consumed by the load, which a proposed technique can not detect [12].It is important to mention that loads are mostly modeled as parallel RLC circuits. The reason for this is mainly because of the high level of difficulty in detecting an island with this type of load; on the other hand, nonlinear loads, such as the loads which produce harmonics or constant power loads, are easier to detect [13].

Based on the technology, islanding detection schemes can be categorized into local and remote strategies. Moreover, local techniques can be classified further into active, passive, and hybrid ones. Figure 4.4 shows the classification of the different techniques based on the technology utilized. This classification is specified in detail in Table 1.2. Although many researchers categorize signal processing techniques as passive islanding detection techniques, studies have shown that signal processing techniques can oIn addition, signal processing techniques have proven that they can adapt to many situations due to their stability, versatility, easy modification, and cost effectiveness [14].

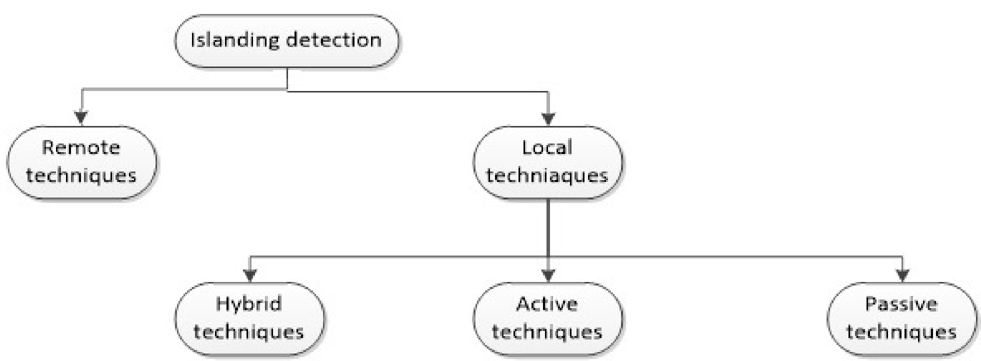


Figure 1.1: Classification of Islanding Techniques.

Table 1.2: Islanding detection methods.

ISLANDING DETECTION	Pros	Cons	Implemented Examples
REMOTE TECHNIQUES	no NDZ	Very Expensive, especially for smaller systems.	Transfer trip scheme (TTS) Power line signaling scheme(PLSS)
LOCAL TECHNIQUES			
Passive Techniques	Fast Does not introduce disturbance. Precise when the difference between generation and load is high	Not accurate when the difference between generation and load low thresholds sitting is a difficult task thresholds sitting is difficult task	Under and over voltage protection or Under and over frequency protection . Detection of voltage and current harmonics
Active Technique	Very Small NDZ	Introduce disturbance in grid. long detection time The perturbation usually decreases the power quality, especially when large enough, thus leading to system instability, even when connected.	Impedance measurement scheme frequency shift Technique
Hybrid Techniques	Very Small NDZ Perturbation is only introduced when islanding is suspected.	Time for Islanding detection is extended because both the passive and active techniques are applied.	Technique based on reactive power and voltage shift.

1.5 Problem Statement

Distributed energy resources, such as wind turbines, internal combustion engines, gas turbines, and photovoltaic cells arise within the current distribution systems. However, the application of the distributed generators (DGs) may introduce problems in proportion to the number that they can solve [15]. For example, the European Commission aims to increase the share of renewable sources to 20 percent of the total by 2020. On the other hand, in the use of renewable energies, many developing economies see solutions to the challenges of rural electrification and a lack of access to electricity [17]. For example, a large proportion of the African population has no access to electricity, even though the continent has a great abundance of alternative and renewable energy sources, such as solar, thermal, photovoltaic energy [18].However, connecting new renewable resources to an electrical grid may cause some problems, such as islanding.

Islanding, as previously defined, refers to the condition in which a DG is isolated from the electric utility but continues to power a local load [19], which creates a lot of problems in power systems. Standards prohibit the DGs from being activated in islanding mode. According to [20], existing standards advise against islanding for the following reasons:

- The effect on Load power quality issues.
- Safety problems and hazards for workers.

- Overloading the DGs.
- The possibility of out-of-phase re-close connection upon reconnecting the system.

Due to the above reasons and many others, it is necessary to identify the islanding conditions and quickly separate the DG from the distribution network. Usually, if there are large variations in loading for DG after disconnecting the main power supply from the grid, then islanding conditions are detected in a straightforward way by observing the numerous parameters, which include frequency change, phase, and voltage magnitude. Nevertheless, in case of minor changes in loading for DG, the conventional islanding detection methods have some trouble in detecting this type of individual islanding condition.

For this study, the present work proposes using passive islanding detection for distribution generators. In this method, the voltage in the network will be calculated and then processed using the signal processing technique to identify the islanding conditions.

1.6 Thesis Objective

In order to accurately detect an islanding condition, a comprehensive research study was conducted on several types of DGs to validate the proposed algorithm. The research objectives can be summarized by the following points.

1. Review the existing islanding techniques in terms of speed, accuracy, complexity, and performance.

2. Propose a novel and accurate islanding detection method by utilizing signal processing techniques.

3. Study the effectiveness of the proposed islanding algorithm and its compatibility with existing standards in terms of speed as well as NDZ.

1.7 Research Methodology

To achieve the above-mentioned objectives, the study methodology is divided into four phases, as discussed below.

Phase-I: Conduct Literature Review

- A review of the importance of the islanding detection and the standards that should be applied in the case of occurrence.
- A general review will be conducted on existing Islanding techniques.
- A review of the signal processing and numerical analysis techniques applied in passive islanding detection.
- A review of the case studies of the systems on which a proposed algorithm can be applied to the validate results.

Phase-II: Simulation and Voltage measurement

- Choosing a test system: a system with wind, hydro, or a combination of wind, hydro, and biomass will be selected to study the effect of islanding on voltage profile.

- Implementing the selected system in an appropriate simulation program to measure the voltage, which is the subject of the study.

- Measuring the voltage on various DGs to verify the proposed algorithm on different types of DGs.

Phase-III: Proposing an Algorithm for islanding detection

- Look for statistical and discriminative features, such as standard deviation, skewness, and correlative relations of the normal cases against abnormal cases.

- Cases which may lead to false detection, such as capacitor switching and motor starting, will be included in the simulations and analysis

- A formulation of the algorithm based on the above steps.

Phase-IV: Testing of the Proposed Islanding Detection Algorithm

- Conduct parametric analysis and assessment of the algorithm to obtain the optimized parameter settings for the algorithm by considering many simulated scenarios to improve the parameters taken in the algorithm.

- Compare results with existing methods.

- Conclusion and tabulating results. Based on the results, conclusions and recommendations will be formulated.

1.8 Thesis Organization

This thesis is divided into five logical chapters. Figure 1.2 explains the methodology in which the method was developed. Chapter 1 serves as the introduction and Chapter 2 covers the background on state-of-the art islanding detection. Chapter 3 contains a theoretical review and a derivation of singular value based islanding detection. Chapter 4 contains several cases of simulated models used to demonstrate the validity of the technique and what typical field values can be expected. Chapter 5 contains the conclusion and future research topics.

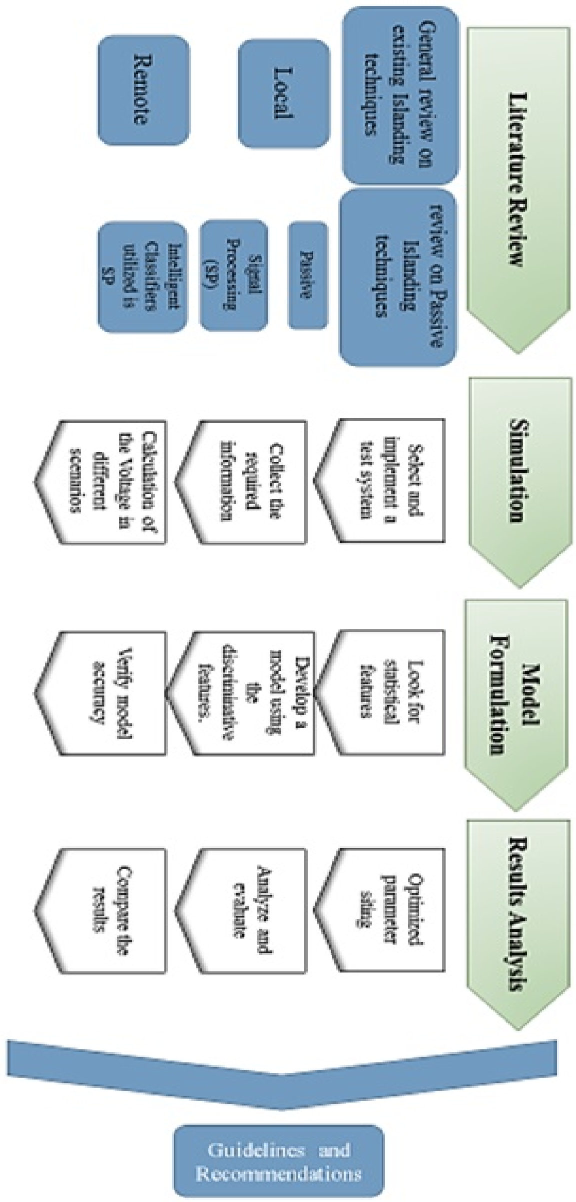


Figure 1.2: Methodology.

CHAPTER 2

LITERATURE SURVEY

Islanding detection is an active instrument for DG protection. There are a variety of schemes and methods being developed for real world practice. In each case, the method has both pros and cons [21–23].The difficulty of comparing one islanding technique with another stems from the fact that each method can work effectively, depending on the situation in which the method is employed. For example, in an inverter-based DG, the frequency shift method, which is related directly to real power variation, works well for islanding detection, whereas a rotating machine responds best to the islanding detection method depending on changes in the terminal voltage, which also corresponds to a change in reactive power. Performance is measured by the ability of the islanding detection method to detect islanding rapidly and accurately. In IEEE 1547 [24]the organization published a standard containing a detailed analysis of the single phase with single source islanding detection methods. Though this testing method is limited to single inverter systems, it is commonly used by standards agencies, such as the Canadian Standards Association and Underwriters Laboratories, as benchmarks to approve grid tie power converter products for sale in North America.

In this chapter, islanding detection methods, which have surfaced only recently, will be discussed and reviewed for their particular pros and cons. Also, based on the technology, the islanding detection methods are categorized into local and remote strategies. Further, local techniques are classified into active, passive, and hybrid ones. However, some researchers categorize signal processing techniques as a different category. These classifications are specified in detail below. Figure 2.1 shows a detailed classification of islanding techniques [14].

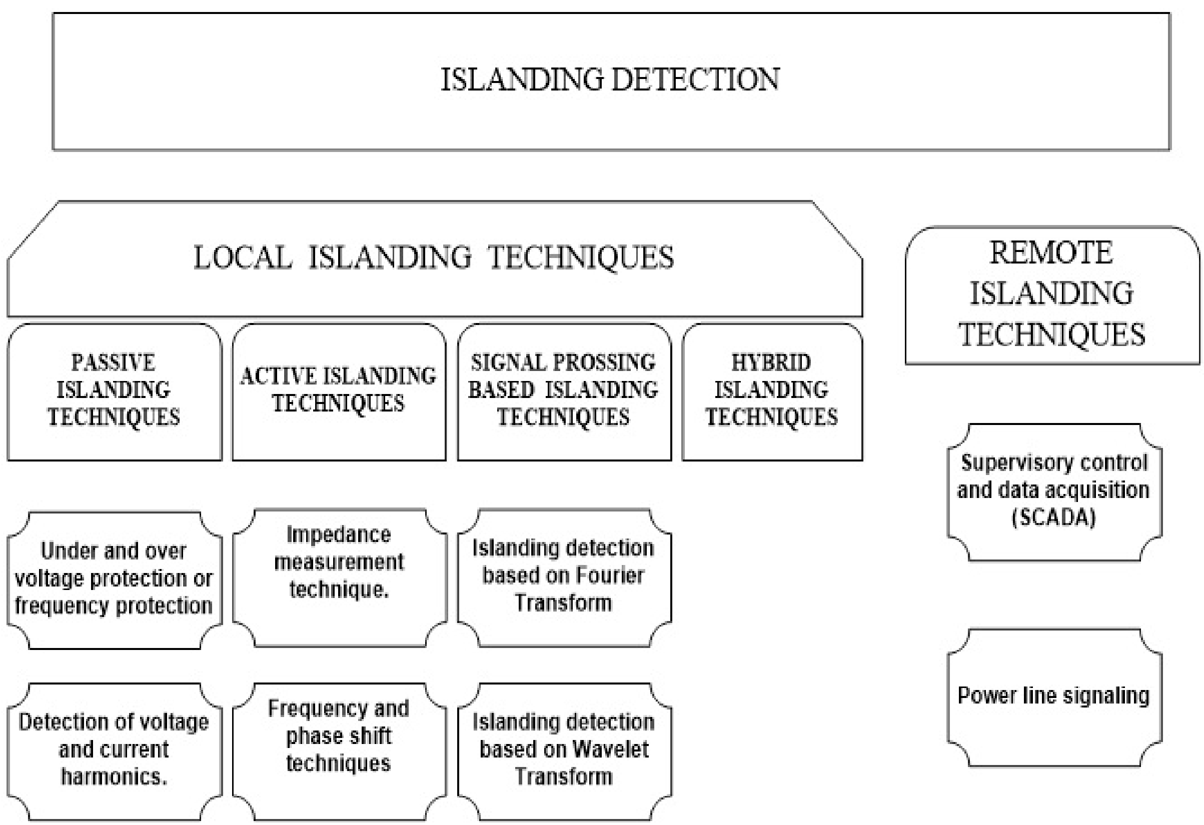


Figure 2.1: classification of islanding techniques.

2.1 Remote Islanding Techniques

Mainly, remote techniques gather the information from the grid via communication channels to establish whether the islanding conditions arise. Most of them have zero NDZ, however, they are very expensive to implement. Below are some techniques which implement communication.

2.1.1 Power Line Carrier Communications (PLCC)

A signal carried through the power line is used in this method. As DGs are interconnected with the distribution network, they are also referred to in this configuration as distribution line carriers (DLC). The main principle of PLCC is simple and practical. A signal generator is positioned at the substation which is directly connected to the distribution network with the DLC. The signal generator is continuously broadcasting signals to the DLCs connected to the distribution grid, and a signal detector at the receiving end detects the transmitted signal. When islanding occurs, the broadcast signal connection is severed and the detector no longer senses the transmitted signal. Therefore, all the DG units are tripped. In some cases, a repeater is needed to amplify the attenuated signal. This happens when the distance is greater than 15 Km [25, 26]. Figure 2.2 shows a scheme for this operating principle.

The mentioned technique is considered to be fast [27]. Because two cycles are required to carry one pulse, the required time to detect islanding is those two cycles. Also, to avoid unnecessary false trips, more than two cycles are used Also,

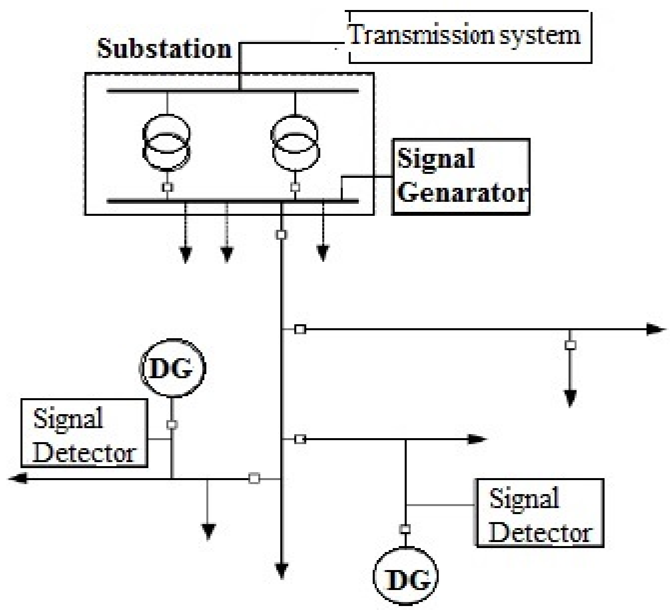


Figure 2.2: PLC-based islanding detection scheme [25]

when four successive pulses go undetected, this is interpreted as islanding. In [28], a transmitter connected to the grid side continuously broadcasts a uni-directional signal to the DGs, which are equipped with a receiver via the transmission line. If any DG fails to receive the transmitted signal, an islanding condition occurs. Figure 2.3 explains the power line signal technique. This method, as the figure shows, can be used for a multi DG system. The main disadvantage of this technique is that it may cause some interference in the system. The major drawbacks of this scheme are: The major drawbacks of this scheme are:

- The cost of implementing such a system on the utility side and the distributed generation side. As is the case with other communication-based methods, no additional wires are needed because a power line is used.

- This method could have a small non detection zones when using a subhar-

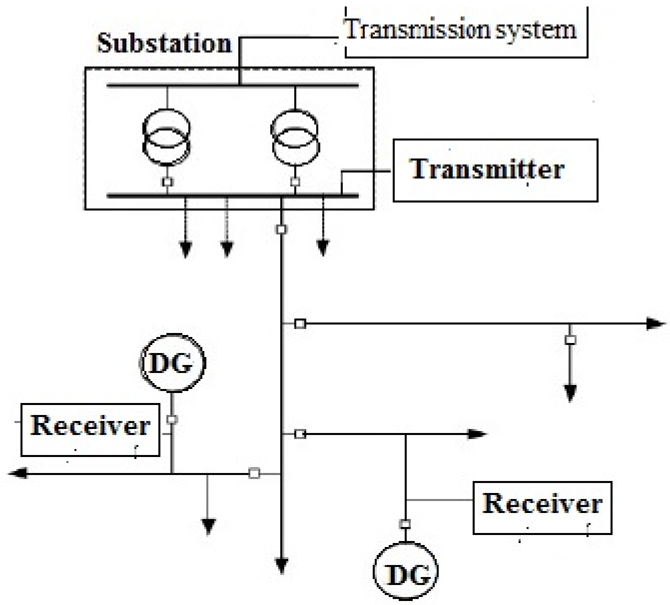


Figure 2.3: power line signaling.

monic signal [26], which is not common for communication based islanding detection schemes; thus it is rarely used.

2.1.2 Supervisory Control and Data Acquisition (SCADA)

In [29]], the SCADA system is utilized to monitor and issue the distributed generation of trip signals . Under this category, the SCADA system is also monitoring all of the distribution generators, not only on the transmission side, but also in sub transmission and distribution, which is not feasible in some cases due to the high cost and depending on the complexity of the grid [23].

2.1.3 Transfer trip schemes

In the transfer trip detection scheme, the circuit breakers are monitored via links to a central control unit. When an interruption is discovered at the distribution substation, the central unit algorithm decides which of the circuit breakers are in an island. Also, it sends the appropriate decision to the DG, and decides whether they should remain connected to the network, or be disconnected. Supervisory Control and Data Acquisition (SCADA) systems can be used for this purpose. Figure 2.4 shows a scheme of this operating principle. This method needs a vast communication support network. Usually, wireless communication

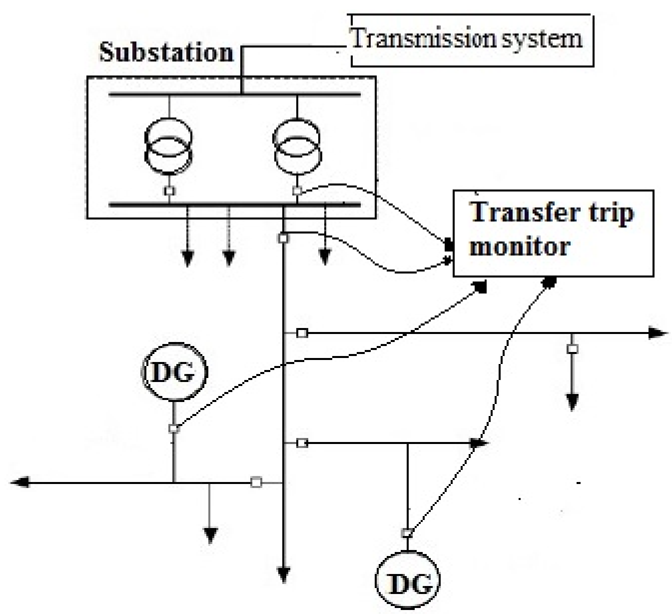


Figure 2.4: Transfer trip scheme.

(radio) or wired communication (leased telephone lines) are the most popular media. A range of different communication resources has recently been introduced, which include proposals to use the Internet (use of a link connected directly to internet web site), optic fibers, Ethernet cables to connect the circuit breaker to the central unit, and satellite communication. Despite their similarities with the communication based detection techniques, they are much more expensive, and the complexity of the design must also be taken into consideration. These drawbacks increase as the grid becomes more complex, which in many cases leads to design reconsideration.

2.2 Passive Islanding Detection

Passive schemes are fast, cheap, and do not affect network integrity; however, in most cases they have a large NDZ. In fact, the main idea utilizes a straightforward measurement, and involves monitoring the voltage or frequency, etc., before then setting a threshold, which determines whether the system is in normal operation or in an islanded condition. It is important to note that islanding causes disturbances that affect the voltage and the frequency, and in many cases, islanding introduces unwanted harmonics. Based on this, a threshold is set (though the threshold value should be chosen carefully to differentiate islanding from other disturbances) to identify an island.

2.2.1 Under and Over Voltage Protection (OVP/UVP) or Frequency Protection (OFP/UFP).

This technique is done through the measuring of voltage or frequency at the point of PCC, which allows the detection of the islanding by setting the limits of normal operation [40].The main idea is to establish a range based on the fact that the reactive and active power consumed by the load will come from the distributed generator and the grid. When the grid is disconnected and the power provided by the generator is greater than of the load, the voltage will increase and vice versa. A violation of the limits indicates islanding. Also, when the reactive power is affected by the system frequency, a sudden change in the system will cause the frequency to change [23].

Despite having a high NDZ, the main advantage of this technique is that it is a low cost solution. In addition, these methods cannot detect the islanding condition when the power of the DG matches the power of the load.

2.2.2 Detection of voltage and current harmonics.

In this method, the harmonics of the voltage signal are measured at the point of common coupling. Next, the harmonics are compared with a certain threshold to examine the occurrence of the islanding condition. Throughout normal conditions, the voltage signal at the DG side is the same as the grid voltage, meaning that the distortion is considered very low and negligible (Total Harmonic Distortion THDv is equal to zero) in most cases. However, when the islanding occurs, the current harmonics come from the inverter and go to the load, in which the impedance is considered higher than the grid. When the current harmonics and the load impedance interact, voltage harmonics are produced. These harmonics can be quantified. Therefore, monitoring the THD of the voltage variants outside the predetermined threshold is considered as islanding [41].This method is considered robust, even under the use of multiple inverter based DGs. However, its effectiveness deteriorates due to grid perturbations, which creates a problem whenever the threshold value is considered for islanding detection. For example, when there is a non-linear load, the distortion of the voltage signal at the PCC can be higher than the threshold value, which may lead to false detection. Moreover, with linear loads, the harmonics variation is sometimes considered lower than the threshold value and the islanded case is considered undetected.

2.3 Active Islanding Techniques

Active islanding detection schemes (AID) are local techniques which mainly depend on introducing a disturbance at the DG side and detecting the islanding condition based on the effect of this disturbance on the voltage and frequency or impedance. AID are very effective and usually have zero NDZ, however, they may reduce the quality of the grid voltage, which in some cases may cause much bigger problems like instability [30]. Some of these techniques are mentioned in the following section.

2.3.1 Impedance Insertion

In this method, an impedance, usually a capacitor bank, is used. Figure 2.5 eexplains the setup of the proposed method. When an island is created for any reason, the power flow is modified, especially reactive power [31].This change will lead to phase change, which will ultimately lead to a change in the resonance frequency. In [32], this method was tested and proven to be highly efficient. Although this techniquehas shown great promise, it has some weaknesses. Some

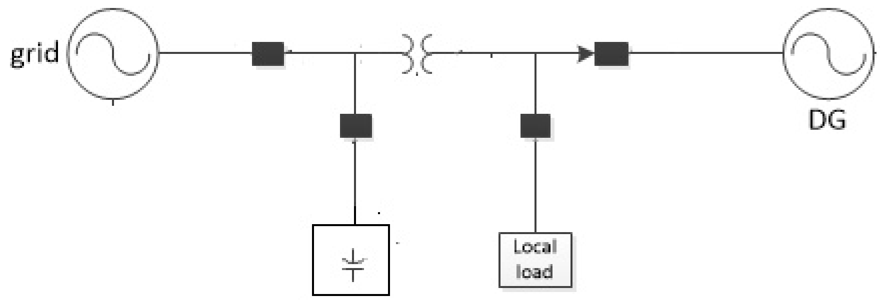


Figure 2.5: Impedance insertion schematic.

of them are related to the high cost associated with connecting a capacitor bank to the system; nevertheless, in some cases, capacitor banks are employed for various reasons, such as to provide reactive power and voltage support. On the other hand, the impedance insertion technique has a low response time due to switching and the delay associated with switching to allow the frequency deviation to be detected, which in some cases violates the IEEE1574 standard. This problem can be solved using appropriately sized capacitors, which can often be inconvenient [32].

2.3.2 Impedance Measurement Technique.

The main concept behind this scheme is quite simple: when an island occurs, the equivalent impedance of the system will change and the islanding condition is detected by monitoring this change. In [33], a semiconductor-controlled rectifier based technology, which draws current, pulses around a zero crossing of the voltage. This is utilized to estimate the value of the impedance, which then determines whether an islanding condition has occurred. Also, [33] states that when an island is created, the impedance of the system usually increases because the grid impedance, which is connected in parallel with the DG, is very small compared with the DG impedance. In this way, the criteria for determining the occurrence of an island becomes very clear. Other techniques can be utilized, such as PQ variation [34], among others.

Although this scheme proved to be robust and to have a small NDZ, its robustness decreases dramatically with the increase of DGs in the grid. Also, it is essential to know the impedance of the grid to set the threshold, and getting the exact value of the grid impedance is often difficult; as a result, this method is inapplicable [35].

2.3.3 Frequency and Phase Shift Techniques

Frequency and phase are highly sensetive to change in the electrical grid, also, when an inverter is connected to the grid, and the grid is an island, a small penetration will result in a significant change in frequency. There are many techniques which employ frequency shift, like the slip mode phase or frequency shift scheme [36], the active frequency drift/shift, and the positive feedback method [37]. These methods usually have a small NDZ, however, they may cause degradation of the power quality of the DG inverter.

Other techniques may involve variations in the active and reactive power. These techniques detect an island by tampering with the active power injected into the system [38].A disadvantage of this method is that it can lead to instability. Another technique injects a current disturbance in the system [39] and monitors its effect on the system. Although these techniques are easy to implement and a have a small NDZ, it is necessary to keep the disturbance signal as small as possible.

2.4 Hybrid Islanding Detection

Hybrid islanding detection employs both active and passive islanding detection methods. An example of these techniques includes those based on positive feedback and voltage balance [42]. These techniques have low NDZ as active techniques, and penetrations are only introduced in the case of of a suspicion of islanding, which is investigated by mimicking passive islanding methods. On the other hand, hybrid detection needs more time over other methods to investigate islanding, which is considered as the main disadvantage of these techniques.

2.5 Signal Processing Techniques.

To improve the passive islanding techniques, signal processing methods are usually implemented. As mentioned in the previous chapter, signal processing techniques have many advantages, such as small NDZ, low cost, and adaptivity. Tools like S-Transform, Hilbert-Huang Transform, Fourier-transform, TT-transform, and Wavelet-Transform are used in islanding detection with promising results and quality performance. In addition, the tools detailed in Table 2.1 can also be used. Some of the signal processing techniques are discussed in detail below.

2.5.1 Islanding Detection Based on Fourier Transform

As generally known, Fourier transform is used in frequency domain signal analysis. It is a representation of the signal by the sum of a sinusoidal wave s; however, as it cannot detect a momentary fluctuation in time, a modified tool of Fourier transform, which involves time-frequency analysis, is implemented in islanding detection. One of the modifications of Fourier transform is the short time Fourier transform (STFT). In principle, STFT divides the signals into stationary frames with a small width. A number of frames are assessed by an assumed moving window. The purpose of the moving window is to identify the relationship between the change in frequency and the time [45] .Another method that utilizes the Fourier principle is that of Discrete Fourier Transform (DFT) for discrete time signals. The main idea behind DFT is to calculate the frequency sequence of a finite length time sequence. It is important to mention that DFT and STFT are not appropriate to analyze non-stationary signals. Usually, grid disturbances, such as transient conditions, are misinterpreted in conventional passive techniques like islanding. Also, NDZ can occur if the power generated matches the load. To overcome these problems, Kim [46] suggested a new method, which utilizes DFT to calculate the 2nd harmonics of the PV system voltage. By calculating the 2nd harmonic coefficients, the controller is prevented from misinterpreting disturbances for islanding conditions. Also, he was able to decrease the NDZ. Kim was able to detect islanding in 1 ms, but Jae-Hung et al. [47] implemented DFT with a Goertzel algorithm to reduce computation time to 2 cycles and to eliminate NDZ.

2.5.2 Islanding Detection Based on Wavelet Transform

Wavelet transform (WT) is used in DSP. It is a scientific modeling of signals derived from two theories: square integral theory and group theory. Unlike FT, WT is a representation of signal in time-frequency domain. As a result, it is much more common in power system applications, such as power quality, protection, feature classifications, and detection [43].Continuous Wavelet transform (CWT) is implemented in islanding detection by analyzing the voltage. This is done by simply using the Mallat decomposition to extract the noise [44].However, this method requires hardware with high computational capabilities to calculate the coefficients. To eliminate this problem, researchers have diverted their attention towards Discreet WT (DWT).

In [20], the authors used DWT on the voltage signal for islanding detection in a wind turbine system. The Daubechies db5 mother wavelet of level five DWT was used to examine the voltage signal, with the method enhancing the islanding detection capability as a result. The proposed scheme was simulated and implemented to verify results concerning elasticity, practicality, and strength.

2.5.3 Islanding Detection Based on S-Transform

The main issue facing island detection based on WT is that this method is noise sensitive and requires batch processing, even though WT extracts the features of the signal in both frequency and time. Stockwell developed S-Transform to overcome the disadvantages of WT and FT. S-Transform is a time frequency tool in which there is a variable window size [48]. Ray et al. [49] applied both S-Transform and Wavelet transform on a system in an islanded condition in a noisy scenario. It was found that S-Transform is a reliable technique under noisy conditions. The disadvantage of S-Transform is that its performance weakens in transient operation.

2.5.4 Islanding detection techniques based on TT-transform

Most non-stationary signals employ time-varying frequency techniques for signal processing. STFT, s-transform, and wavelet, which are the most famous techniques, use the same principle. However, the aforementioned transform techniques also introduce redundancy by transforming a 1-dimensional time signal (1D) to a 2D time scaled (or time-frequency) signal. In 2003, a new technique emerged which was developed from s- transformthe time-time transform (tt-transform). It contains redundancy in time passing from a 1D time signal to a 2D time and time signal [50, 51]. Aziah et al. [52] proposed a technique using tt-transform (in which a 2D transforma- tion time plot of the original signal is presented) for islanding detection. Results showed that the proposed technique is able to detect the islanding condition in a faster and more accurate way. It was able to do so because each event possesses a unique and distinguishable pattern. In [53], TT-transform is used to extract a deterministic feature for islanding detection. Other jagged islanding is based on the extracted features and then compared. The results obtained are with wavelet and s-transform. It was found that the other techniques are inferior techniques for islanding detection in most cases.

2.5.5 Islanding detection techniques based on Hilbert Huang transform (HHT)

HHT is considered a unique signal processing technique. HHT involves two stages. In the first stage, a decomposition of the tested signal is conducted. The signal is broken down to an intrinsic mode function (IMF) that has representative and instantaneous frequencies with corresponding amplitudes through the use of the empirical mode decomposition (EMD) procedure. In the second stage, the intrinsic mode functions are arranged from the function with the largest frequency to the function with the lowest frequency. Hilbert transform is then used on each function of the IMF, resulting in the instantaneous frequency with the amplitude versus the time. This arrangement in which the EMD process is combined with Hilbert transform is called the Hilbert Huang transform (HHT) [54, 55].The advantages of this method over wavelet transform, STFT, and s-transform are discussed in detail in [56–58]. In [59], a suggested approach for passive islanding detection implemented in inverter based DGs is discussed, which utilizes HHT for features mining. The simulation results showed that the proposed method detects islanding in two cycles or less. Table 2.1 is a summary for the islanding detection techniques which use the discussed signal processing methods.

Table 2.1: Classification of Signal Pressing Techniques.

SP technique	Example	Method used	Examined system	Detection interval	Pros & Cons
Fourier transform	Kim [46] Jae-Hyung [47]	DFT DFT(Goertzel Algorithm)	PV Single phase 2 stage PV PCS	Around 1 ms Less than 2 cycles	Robust control against grid disturbance Fast harmonic computation
Wavelet transform	Karegar [20]	DWT	IG type wind turbine	Less than 0.2 s	More reliable
s-transform	Ray [49]	s-transform	Inverter based	26–28 ms	S-transform is most efficient but WT fails under noisy condition
tt-transform	Mohanty [60]	TT-transform	Hybrid (PV, Fuel cell, wind)	—-	Best in a noisy environment
Hilbert Huang transform (HHT)	Mohammadzadeh [59]	HHT	Inverter based DG	Less than 2 cycles	Efficient, simple and robust against noise

2.6 Intelligent Classifier Implementation associated with Signal Processing

Up to this point, the islanding detection techniques have been implemented using only signal processing tools, which were introduced earlier. In order to take a decision, the signal processing based islanding detection technique depends on extracting the desired features from the signal, and through making comparisons with specific threshold values. Choosing a value for the threshold is considered a very difficult task. If it has a high value, then disturbance will go unnoticed, whereas if it has low value, then it will detach the DG link to the grid, even in the case of disturbances other than islanding. To solve this problem, a new method is suggested where intelligent classifiers and signal processing-based islanding detection techniques are combined. Intelligent classifiers are usually used with signal processing based islanding detection techniques. Examples of techniques that can be used as a classifier instead of a threshold setting include the adaptive neuro fuzzy inference system (ANFIS), the artificial neural network (ANN), the probabilistic neural network (PNN), random forest (RF), the support vector machine (SVM), and Fuzzy logic control. These intelligent classifiers improve speed, efficiency, and accuracy, and can additionally detect islanding without any threshold settings, such as popular passive based on signal processing. The methodology behind these techniques is explained in Figure 2.6.

Guiliang [61] suggested a new method for islanding detection. Based on FFT, the

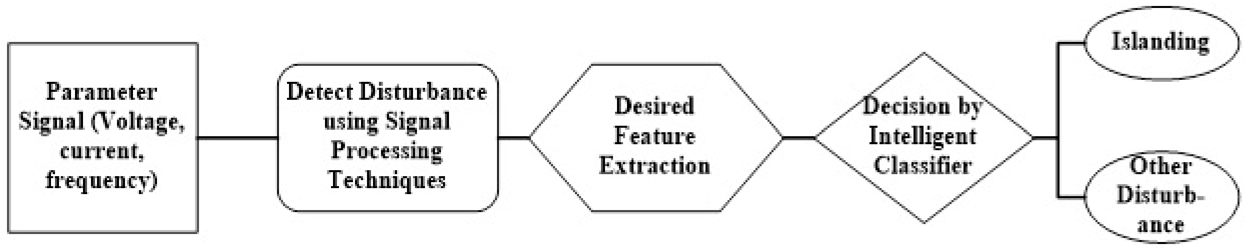


Figure 2.6: Block diagram of signal processing based technique with an intelligent classifier.

desired features are extracted and then passed through an artificial immune system (AIS) as the intelligent classifier, respectively. On the basis of the simulation results, Guiliang was able to verify that his proposed scheme is very efficient. The issue with this method is that it needed a complicated and developed digital signal processor (DSP) for it to be implemented. In [62] and [63], the researchers used an intelligent classifier, along with the discreate Fourier transform, to improve the passive islanding detection scheme proposed in the paper. Guiliang also employed the same process and achieved similar results. Kar and Samantaray [62] extracted twenty seven features using DFT in order to train a data mining model for islanding detection. The data mining model consists of three different intelligent classifiers: random forest (RF), a decision tree (DT), and a support vector machine (SVM). The proposed scheme was investigated by considering the inverter and synchronous machine-based DG in the micro-grid system. In that paper, a comparison between the accuracy of the aforementioned intelligent classifiers was made. The accuracy of SVM and RF was very similer to DT, but the implementation of DT on a commonly used microprocessor is much easier compared with RF and SVM. The proposed scheme detects the islanding condition in less than 1.5

cycles. The decision tree model was also compared with [70], that the proposed method has more accuracy when making assessments, and seriously impacts decision boundaries, which also provides a more generalized solution to both cases. Synchronous and inverter-based DG, as compared to the existing intelligent anti-islanding models are only based on synchronous-based DG [64]. AbdElkader et al. [63] processed the voltage and current signals with a discrete Fourier transform to extract the second harmonic components. The second harmonic values are then fed to the artificial neural network (ANN) for decision making. This proposed passive method, which is implemented for double fed induction generator (DFIG) based wind turbines, detects the islanding condition within 2 cycles and does not indicate a power mismatch range in the undetected region as long as the load values are within the prescribed limits. As the literature suggests, the use of intelligent classifiers enhance detection time performance and accuracy.

2.7 Summary

This chapter has covered the background topics that are relevant to the topic of this thesis. These topics are: islanding detection techniques, signal processing islanding detection techniques exploited in islanding detection, and intelligent classifiers associated with islanding detection techniques. The literature showed that signal processing techniques overpass other islanding detection techniques, such as remote techniques, which are expensive and not realizable in some cases. Also, signal processing techniques do not introduce any disturbances in the grid, which may lead to power quality issues such as those found in remote techniques, and they also have small NDZs, unlike passive techniques. Another advantage of signal processing techniques is that they do not require threshold fitting if intelligent classifiers are used. Literature shows that islanding detection techniques, such as Fourier transform, S-transform, and others are implemented for a single type of DG. They also vary with performance in terms of detection time, robustness, and NDZ. This thesis aims to find the quickest and best performing signal processing based islanding detection technique which can serve different types of DG.

CHAPTER 3

PROPOSED ISLANDING DETECTION METHOD

3.1 Introduction

This chapter contains a description of the proposed islanding detection method for distributed generation. Singular value analysis for islanding detection is a novel form of signal processing detection technique. The SVD islanding detection technique operates based on the principle that a disturbance has a direct effect on the singular values. Also, in order to test the proposed method, three case studies were considered. These experiments provided insight into the existing interconnected distribution systems. The live islanded state measurements have been simulated in MATLAB simulations that closely match the existing network. To fully understand the concept of SVD islanding detection, this chapter discusses the proposed islanding detection method description.

3.1.1 Stage 1: Simulation of the test system

In the first stage, a test system was simulated by using PowerSim in Simulink MatLab, where the voltage is recorded. Load modeling for the purpose of testing is discussed below.

Load Modeling.

Islanding detection with nonlinear loads, such as loads that produce harmonics or constant power loads, are easy to detect [65]. On the other hand, in many cases the loads are modeled as a parallel RLC circuit, which depends on voltage and frequency. This type of loading makes it difficult to detect islanding. In this work, and for all of the studied islanded cases, the load is represented as an RLC circuit. The active and reactive powers of the load are given by

$$P = P_0(1 + K_{fp}\Delta f + K_{vp}\Delta V) \tag{3.1}$$

$$Q = Q_0(1 + K_{fq}\Delta f + K_{vq}\Delta V) \tag{3.2}$$

Where P, and Q are the active and reactive power when a new voltage and frequency are introduced. P_0, and Q_0 are the active power and reactive powers at nominal voltage and frequency, K_{fp}, and K_{fq} are the frequency coefficients of active power and reactive power of the load, K_{vp}, and K_{vq} are the voltage coefficients of active power and reactive power of the load. ΔV is the voltage deviation, and Δf is the frequency deviation. In addition, starting a large motor or switching a capacitor bank is a different type of loading, which could lead to the false detection of the islanding detection algorithm. This, in turn, may lead to further problems such as instability. Therefore, it is important to study the effect of motor starting and capacitor charging on the islanding algorithm.

3.1.2 Stage 2: Formulation of voltage matrix

In this stage, a matrix X is formed whereby the rows of the matrix represent a cycle of the voltage. The number of samples per cycle (n) is fixed at 1000 samples, as shown in Equation 3.3. The reason for this will be explained later in chapter 4.

$$X = \begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1j} & \dots & x_{1n} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2j} & \dots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & x_{ij} & \ddots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & \dots & x_{mj} & \dots & x_{mn} \end{bmatrix} \tag{3.3}$$

Where x_{ij} represents sample j from cycle i and m is the number of cycles processed through the algorithm at a time. Different numbers of cycles were tried in order to come up with fast and reliable results.

3.1.3 Stage 3: SVD analysis

In the third stage, the singular values of matrix X are calculated. These singular values are directly proportional to the variances in the principle components of matrix X [48]. In the following subsections, principal component analysis and singular value decomposition are discussed in detail. Based on a certain criterion, the number of singular values are chosen.

Principal component analysis

Principal Component Analysis (PCA) is a mathematical method in which underlying calculated principles are exploited to transform a specific amount of correlated data into a smaller number of components called principal components, which are essentially an orthogonal basis of the original data. The origins of PCA lie in the multivariate analysis of a data set. However, PCA has many other applications. PCA is called "one of the most important results from applied linear algebra" [67] and it is also commonly used when trying to analyze large data sets. Some of the other common applications include data compression, blind source separation, and de-noising signals. PCA employs a vector space transformation to decrease the dimensionality of a data set using the principle of projection. For a specific data set, which may contain many variables, it is presented in fewer variables (the PCs). Because of that, it is often used as a tool for reducing the dimension of a data (the PCs) set. Thus, this allows the analyst to conveniently spot patterns, trends, and outliers in the data, which is useful in the present work.

Singular Value Decomposition (SVD)

The SVD is a generalized form of matrix diagonalization. SVD can be defined as a method for converting correlated data into uncorrelated singular values, in which the difference between the original data is better exposed. Also, SVD can identify and order the dimensions along the data points that show the most dissimilarities. Since SVD identifies the location of the maximum variation, it is used to find the best approximation of the data [68]. Any $m \times n$ rectangular matrix A can be decomposed as follows:

$$A = USV^T \tag{3.4}$$

Where:

- U and V are orthonormal matrices, corresponding to m and n-dimensional rotations, respectively.
- S is an $m \times n$ diagonal matrix with diagonal elements σ_k called singular values, which are non-negative and arranged from largest to smallest. They can be interpreted as stretching factors along the rotated coordinate directions. If the rank of A is r, there are r positive σ_k ; other singular values are zero. $r \leq min(m, n)$.
- The columns U_k of U (called the left singular vectors) are the eigenvectors of the $m \times m$ symmetric matrix AA^T.
- The columns V_k of V (called the right singular vectors) are the eigenvectors of the $n \times n$ symmetric matrix A^TA.
- The σ_k are the eigenvalues of both AA^T and A^TA.

In this work, the singular values of a DGs output voltage estimation, with and without islanding conditions, are used to determine the islanded conditions.

3.1.4 Stage 4: Training and testing ANN

In this stage, the chosen singular values are used to train and test an artificial neural network (ANN) to determine the islanding condition. The following section gives a description of ANN architecture and training.

The ANN Architecture.

AANN is a common statistical learning algorithm in data mining. The basic idea of ANN was inspired by the biological neural networkthe human brain. The human brain is composed of a vast number of different neurons, which are interconnected in an incredibly complex way. ANN has a similar structure to the human brain; that is, it predicts events by learning new information and stores it within the neurons by interchanging connections and weights [69]. For many complex problems which are hard to solve by traditional computation methods, ANN might be a good idea to replace them. In general, it is difficult to find a single criterion to differentiate islanding events from other non-islanding events just by looking into the singular values. As such, this paper uses a well-used type of neural network model, which is known as feed-forward back-propagation network (BP network) [70] for developing an accurate islanding detection technique. Figure 3.1 shows the basic architecture of a feed-forward back-propagation network. The ANN has a three-layer architecture: input nodes, hidden nodes, and output nodes. Each node (neuron) in one layer is connected to each node in the next layer. The number of nodes in the input layer is the same as the input features in the training dataset, and the number of nodes in the output layer is the number of outputs (in our work, we only have one output which is "islanding"). The number of hidden nodes in the middle layer is normally between these two numbers. It is worth mentioning that the number of hidden nodes is very important because both over-fitting and under-fitting will cause poor training results. Figure 3.2 demonstrates the structure of a node. From Figures 3.1 and 3.2, the neural network mechanism is described as follows: the nodes in the previous layer send a signal into the next layer, and then a separate weight value is used to multiply each of these signals. Then the summed weighted inputs are passed through a limiting function which limits the output in a fixed range (generally is between 0 and 1). The limiter output is then transmitted to the nodes in the next layer [74].

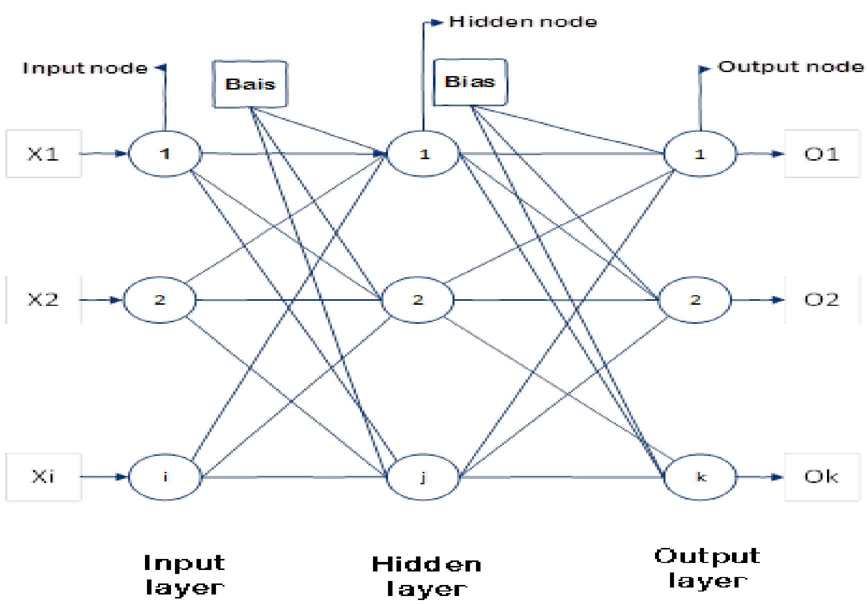


Figure 3.1: Basic neural network structure of BP network

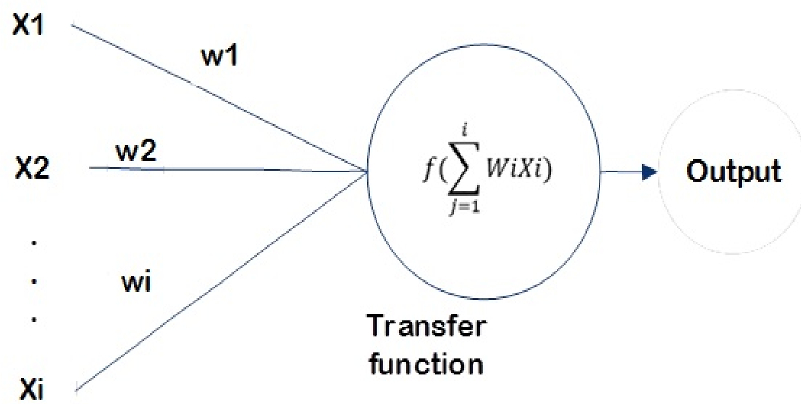


Figure 3.2: Basic structure of a node

Neural network training

In the training process of a neural network, Back Propagation (BP) is used. BP is a learning algorithm which is considered the most common in the feed forward ANN networks due to its simplicity and validity. In order to train the ANN using this method, a set of data where the outputs are known must be provided. The behavior of the network is decided using these sets of data. The BP learning process can be summarized by the following steps:

1. At the start of the training process, the singular values are fed to the ANN, and output is randomly generated based on the initial value of the weight of the ANN. Then, the mean squared-error (MSE) is calculated for each neuron output.

2. The error values are then propagated backwards through the network. The weights are modified using the sigmoid transfer function, which determines

the output of hidden-neuron (Equation 3.5) and the output of output-neuron is modified through pureline function (Equation 3.6) [71].

$$f(x_i) = \frac{1}{1 + exp(-\sum_{j=1}^{n} x_i w_{ij} - \Theta_{ij})}, \quad i = 1, 2, \ldots, n \tag{3.5}$$

$$f(x_k) = \sum_{j=1}^{n} x_j w_{jk} - \Theta_{jk} \tag{3.6}$$

Where, x_i is the input value, W_{ij} is the connection weight between the $j'th$ hidden neuron and $k'th$ the input neurons. W_{ik} is the weight between the output neuron and the hidden ones, respectively,θ_{ij} and θ_{jk} are bias terms for the $j'th$ and $k'th$ neuron, respectively; i,j, and k are the number of neurons in each layer.

3. The whole process is repeated for each of the training cases until the overall error value reaches the predefined value.

To train the ANN, different islanding situations were simulated in Matlab along with other disturbances (such as capacitor switching and motor starting), which can be misinterpreted as islanding. Furthermore, different loading conditions are taken into account in order to identify the patterns of islanding which affect the voltage waveform. After calculating the singular values of each case, a ten-cycle singular value for every case is considered to train the ANN. In the present work, three different test systems are implemented. The ANN for each system is trained separately. Figure 3.3 shows the flow chart of the proposed stages of the islanding detection method.

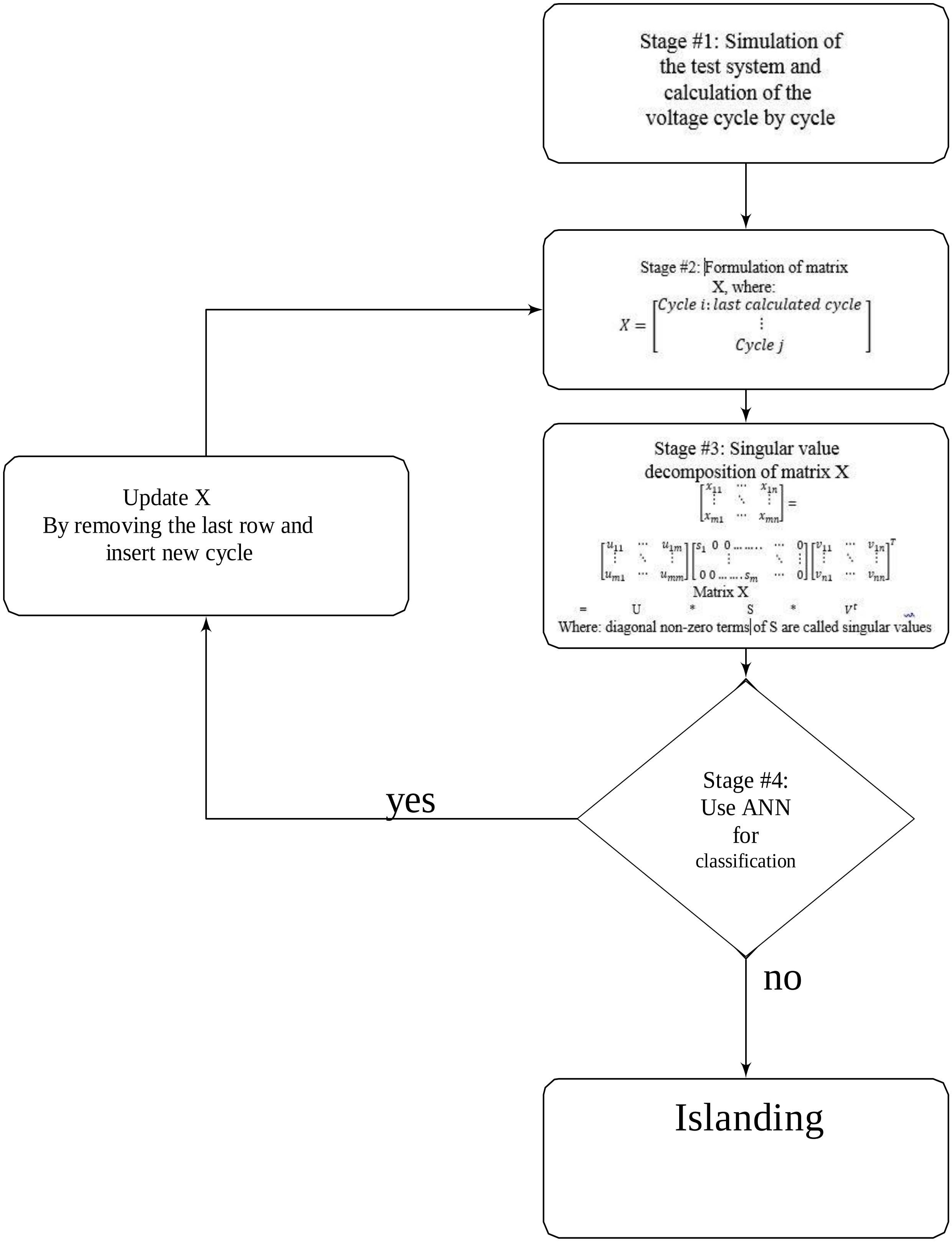


Figure 3.3: flow chart of islanding detection method

3.2 Test systems

In order to properly validate the method of the SVD technique for islanding detection, three practical case studies were considered. These cases were selected to cover a spectrum of DG systems. The three different systems are described below.

3.2.1 System 1: A small induction motor based wind turbine unit [20]

Figure 3.4 shows a schematic diagram of a small wind turbine unit. In the distribution system, the DG unit is a wind turbine induction generator, which is connected to a capacitor bank to improve the power factor. The wind turbine feeds a local load, which is a three-phase parallel RLC before the main circuit. "r" denotes the series resistance and L is the series inductance. The induction generator rating is 2 MVA/400V at 60Hz frequency.The load is modeled as RL circuit with variable size in order to test the algorithm for many scenarios.

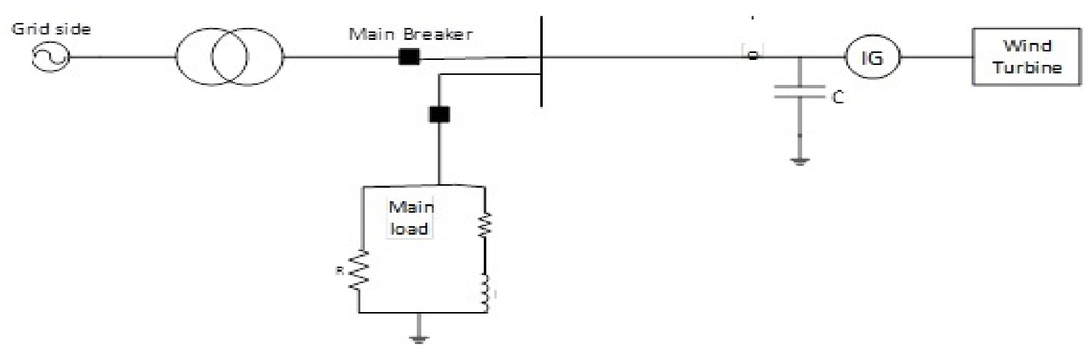


Figure 3.4: How the wind turbine connects to the grid

3.2.2 System 2: A 9 MW wind farm consisting of six 1.5 MW wind turbines [63]

A 9 MW wind farm consisting of six 1.5 MW wind turbine generators linked to a distribution system (25 kV voltage level) was implemented. The wind farm exports power to the electrical grid via a distribution network and feeds the local loads. Figure 3.5 shows the system used in simulation. Wind turbines use a doubly-fed induction generator (DFIG) as a generator containing a wound rotor induction generator and an AC/ DC/AC insulated gate bipolar transistors IGBT-based pulse width modulator (PWM) converter. The stator is linked directly to the 60 Hz network, while the rotor winding is connected to a variable frequency through the back to back converter. The DFIG topology makes it possible to maximize the energy produced from the wind turbine, even at the lowest wind speeds, which is done through the optimization of the wind turbine speed and through the minimization of the mechanical stresses on the turbine throughout gusts. A step-down (120/25 KV) transformer rated 47MVA, 60 Hz connects the distribution grid to the network. The wind farm transformer ratings are 10MVA, 60 Hz, 575 V/25 KV, as shown in Figure 3.5. The load is modeled as RL circuit with variable size in order to test the algorithm for many scenarios.

3.2.3 System 3: 11kV Malaysia distribution network [72]

This system is implemented in a 11 kV distribution system which exists in the Malaysian grid. It contains 2 mini-hydro distribution generator units and

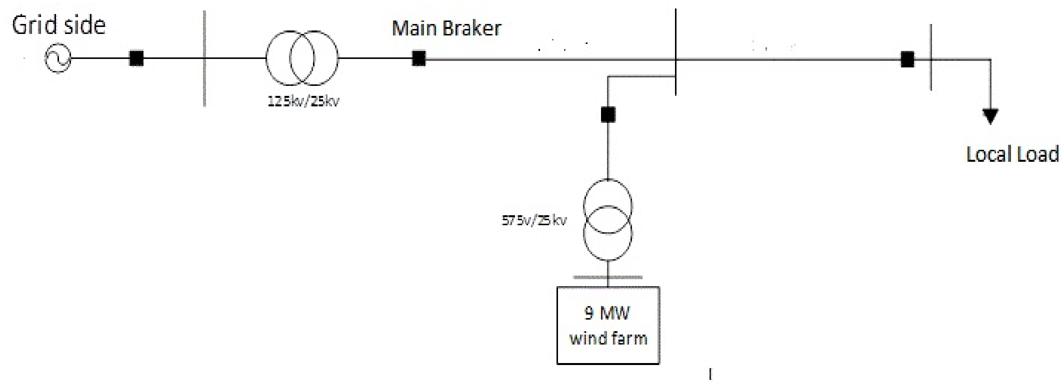


Figure 3.5: 9 Mw wind farm.

1 Bio-Mass distribution generator unit forming a hybrid distribution network having three DG units. This system, as shown in Figure 3.6, is modeled in MatLab Simulink software. Table 3.1 shows the values of the load at each bus. Two 30MVA transformers each connects the 132 kV transmission grid to the 11kV distribution network. Opening the main circuit breaker in Figure 3.6 simulates islanding. A model description of the various components used in the simulation is also described. The tested system has two mini-hydro units rated

Table 3.1: Load parameters.

Bus #	P (MW)	Q (MVAR)	Bus #	P (MW)	Q (MVAR)
1013	0.07	0.05	1010	0.1383	0.05
1026	0.1	0.05	1044	0.1488	0.05
1018	0.1743	0.09	1050	0.1095	0.05
1020	0.2745	0.1	1057	0.189	0.09
1004	0.2121	0.09	1058	0.198	0.09
1012	1.9	0.65	1151	0.2218	0.05
1047	0.1179	0.05	1039	0.1	0.05
1046	0.2535	0.1	1029	0.3468	0.1
1019	0.191	0.05	1154	0.21	0.09
1141	0.097	0.05	1056	0.3475	0.1

2MVA with capability to supply 1.8 MW. The unit operates at a voltage level of 3.3 kV. A synchronous generator is connected to a hydraulic turbine, a governor,

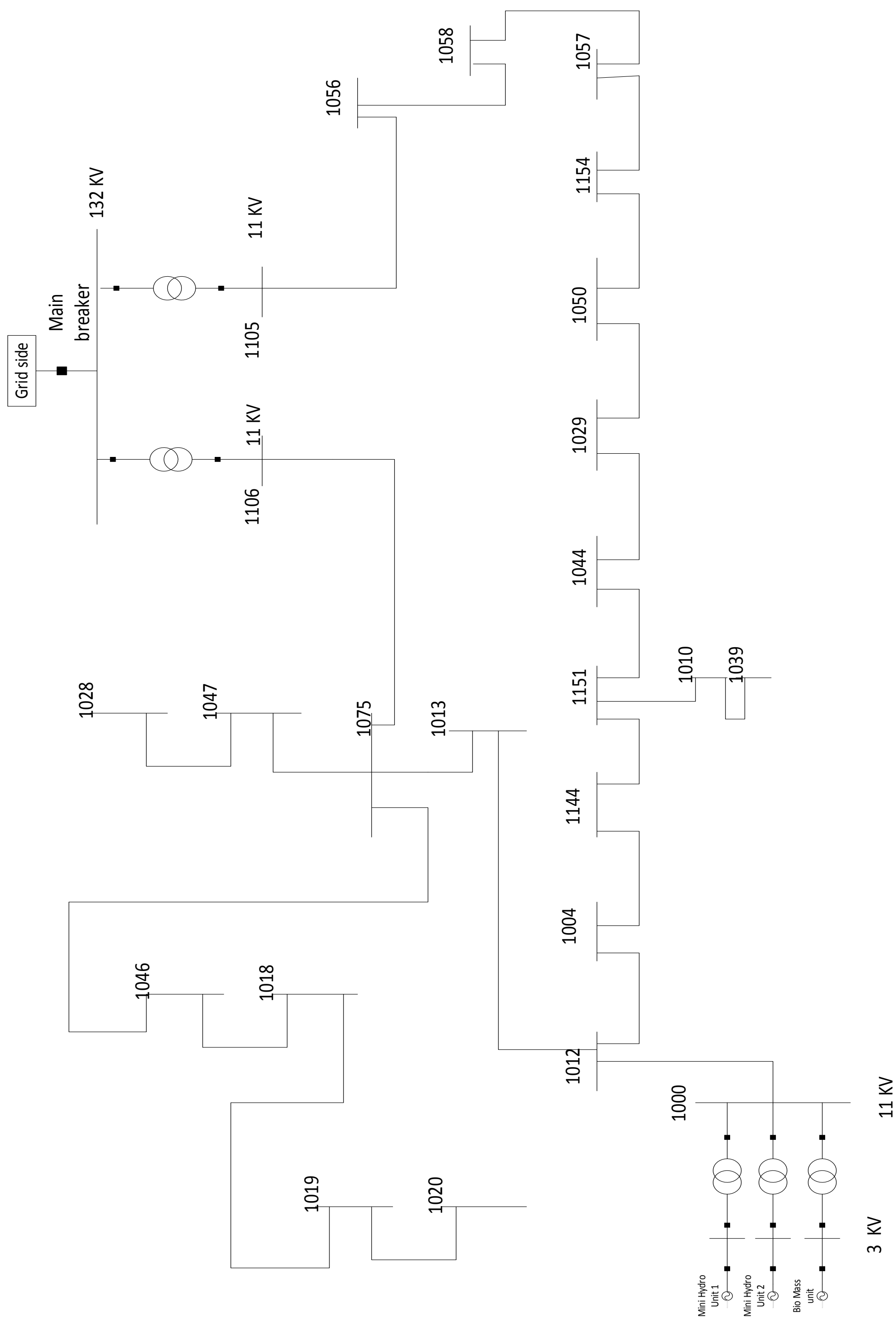
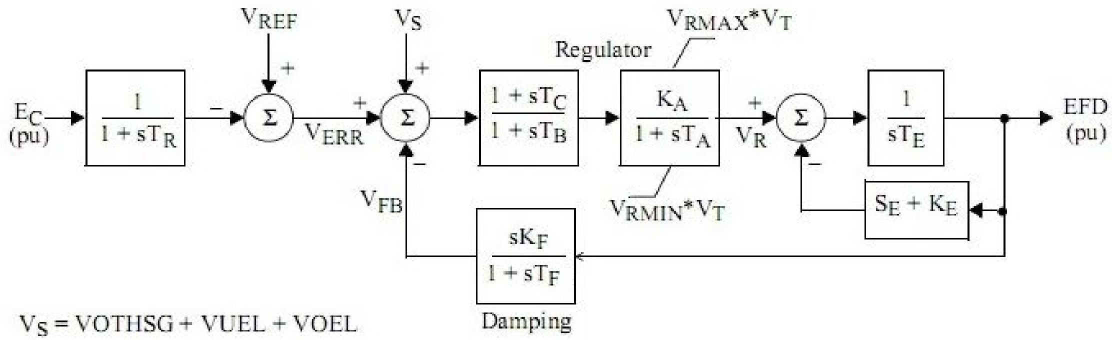


Figure 3.6: 11kV Malaysia distribution network



TR	Seconds	Filter time constant
TB	Seconds	Voltage regulator time constant
TC	Seconds	Voltage regulator time constant
KA	pu	Voltage regulator gain
TA	Seconds	Maximum voltage regulator output
VAMAX	pu	Minimum voltage regulator output
VAMIN	pu	Minimum voltage regulator output
TE	Seconds	Exciter time constant, integration rate associated with exciter control
KF	pu	Excitation control system stabilizer gains
TF	Seconds	Excitation control system stabilizer time constant
KC	pu	Rectifier loading factor proportional to commutating reactance
KD	pu	Demagnetizing factor, a function of exciter alternator reactances
KE	pu	Exciter constant related to self-excited field
SE	pu	Exciter saturation function value at the corresponding exciter voltage,
VRMAX	pu	Maximum voltage regulator outputs
VRMIN	pu	Minimum voltage regulator outputs

Figure 3.7: IEEE AC1A exciter parameters

and an excitation control to form the hydro unit.

Mini-Hydro Unit

The two hydro generators are connected to a step up transformer (3.3kV/11KV) rated 2 MVA. An IEEE type AC1A exciter standard model is used in the system with typical parameters, see Figure 3.7 . Table 3.2 shows the parameters chosen for the exciter. A PID control unit is used to control the governor and turbine with values shown in Table 3.3, see Figure 3.8.

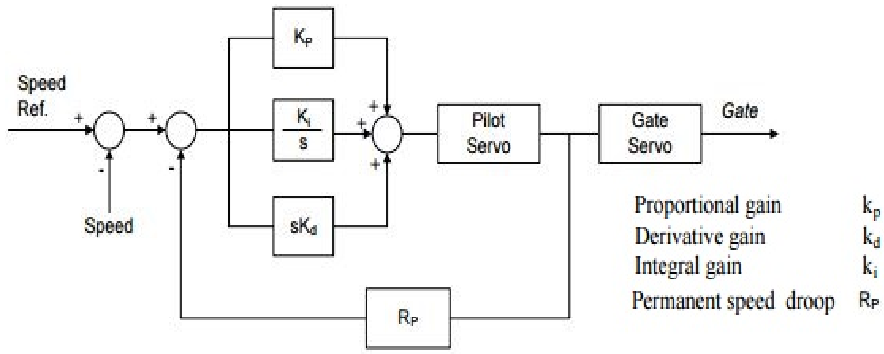


Figure 3.8: Governor and hydraulic turbine model

Table 3.2: IEEE AC1A exciter parameters

Parameter	Value	Parameter	Value	Parameter	Value
T_A	0.02	T_B	0	T_C	0
T_E	0.8	T_F	1	K_A	400
K_C	0.2	K_D	0.38	K_E	1
K_F	0.03	V_{Amax}	14.5	V_{Amin}	14.5
V_{Rmax}	6.03	V_{Rmin}	5.43	$SE(VE_1)$	0.1
$SE(VE_2)$	0.03	VE_1	4.18	VE_2	3.14

Table 3.3: Hydraulic governor and turbine parameters.

Parameter	Value	Parameter	Value	Parameter	Value
TA	0.050	KI	0.350	flower gate position	0.000
TC	0.200	KD	0.900	gate opening	0.160
TD	0.010	RP	0.0400	gate closing	-0.160
KP	2.000	ceiling gate position	1.000	KA	0.330
TW	0.050	D	0.350	Initial power	0.750

Bio-Mass unit

Bio-Mass DG unit has a rating of 2 MVA with power dispatch of 1.85 and operates at a voltage level of 3.3 kV. The Bio-Mass unit is connected with 2 MVA step-up transformer (3.3/11 kV). The DG unit consists of an asynchronous generator along with a thermal governor and a turbine. The same exciter model and parameters used for the hydro units is used also for the Bio-mass unit. The governor and turbine model parameters are shown in Tables 3.3 and 3.4.

Table 3.4: Mechanical governor and turbine parameters.

Parameter	Value	Parameter	Value	Parameter	Value
Permanent droop(R)	0.05 p.u	Speed turbine time constant T2	0s	Coefficient of inertia H2	1.5498s
Regulator gain Kp	1	Speed turbine time constant T3	10s	Coefficient of inertia H3	0.24894s
Dead zone	0	Speed turbine time constant T5	0.5s	Coefficient of inertia H4	0s
Max. CV opening rate	.1 p.u/s	Turbine torque fraction F2	0.5	Coefficient of inertia H5	0s
Min. CV opening rate	-0.1 p.u/s	Turbine torque fraction F3	0.5	Damping factors D2	2.1 pu T/pu dw
Speed relay time constant Tsr	.0001s	Turbine torque fraction F4	0	Damping factors D3	.4 pu T/pu dw
Speed relay time constant Tsm	.15s	Turbine torque fraction F5	0	Damping factors D4,5	0 pu T/pu dw

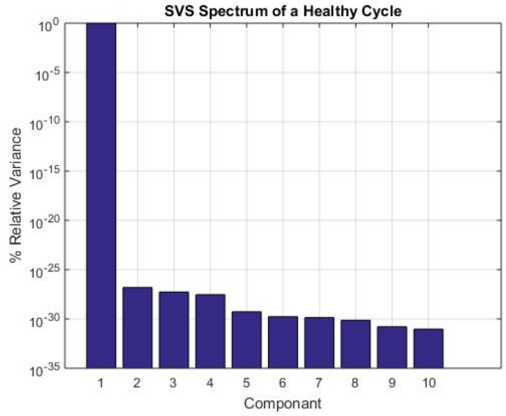
CHAPTER 4

RESULTS AND DISCUSSION

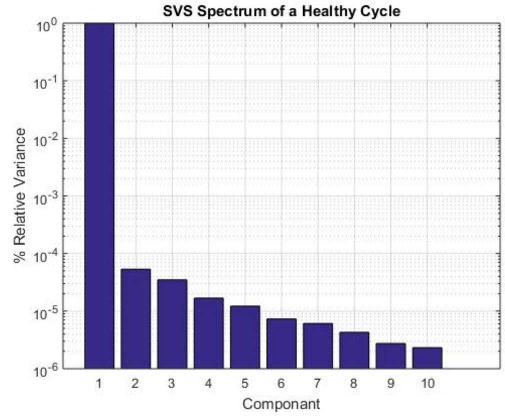
This work studies the islanding effect on the decomposed voltage signals. The diagonal of matrix S (i.e., si) represents the singular value spectrum (SVS), where SVS can be imagined by using scree plots, as proposed by Cattell in 1966 [73].The weight of any singular value is an indication of its importance. Furthermore, the variance is relatively proportional to the squared singular value, as explained in section 2.3. The relative variances $\sigma_i^2 \sum[\sigma_k^2]$ when plotted, forms a scree plot. Cattell suggested the use of a graphical method to choose the significant components. In this section, the effect of the abnormal grid operation on singular values is exploited to form the islanding detection algorithm. Further discussion is demonstrated below.

4.1 Healthy case

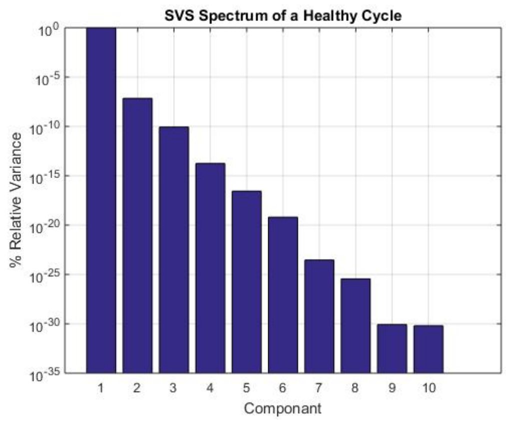
For the three systems under study, Figure 4.1 shows the relative variances of ten cycles without any disturbance in the grid. The first component has the greatest



(a) system 1



(b) system 2



(c) system 3

Figure 4.1: relative variances for a healthy case .

value which approaches one. This means that the other values are considered noise in the grid. It is worth mentioning that in figure 4.1b, the components (from 2 to 10) have higher values than the ones in both Figures 8b and 4.1c. This is expected due to the noise generated by the inverter.

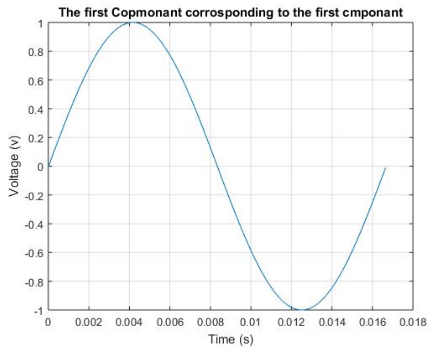
Figure 4.2 shows the reconstruction of the healthy cycle by eliminating the effect of secondary components. The reconstruction of a cycle while depending only on the first singular value, returns the same cycle. This is expected because the major component can be considered as a denoised voltage cycle.

4.2 Islanding case

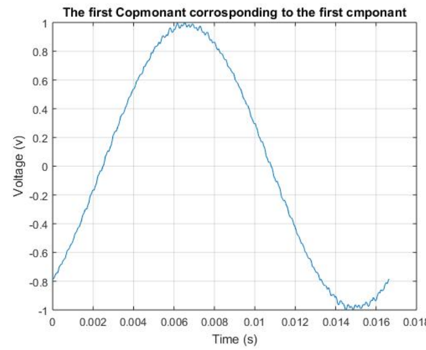
For system 1, and under the islanding condition imposed at cycle 120, Figure 4.3 showed a considerable increase in singular values as compared to the first one. For the three systems under study, figure 4.4 shows the simulation results when all of the systems are tested at nominal rating for the RLC loads under normal and islanding operating conditions. It can be noticed that the first singular value is eliminated as it does not show any significant changes. Comparing Figures a1 and a2, b1 and b2, and c1 and c2, shows that the secondary singular values (2 to 10) are greatly increased under islanding conditions. Careful examination of the 7th onward singular values shows that they are of much lower magnitudes. Therefore, singular values from the 7th to the 10th component are treated as noise, and are hence considered negligible. As such, the present work proposes monitoring the variation of the secondary singular values (from only 2 to 6).

4.3 Training ANN

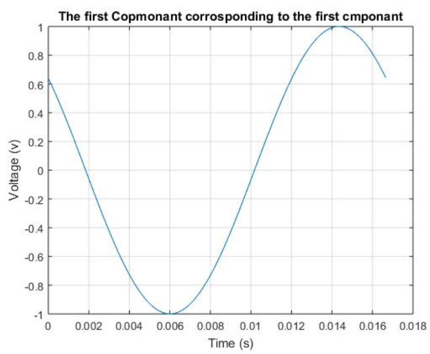
The ANN used in our proposed method is the MLP (multi-layer perceptron) with five neurons in the first layer and one neuron in the output layer.For the hidden layer different number of neurons were tested for the hidden layer. It was found that we achived the best performance when the number of hidden neurons was one, which is recommended by [74]. For each system, the ANN is trained separately for eight different scenarios: nominal loading, an increase and decrease of islanding at nominal loading, an increase and decrease of 20% both under islanding and no



(a) system 1



(b) system 2



(c) system 3

Figure 4.2: The reconstruction a healthy cycle using SVD

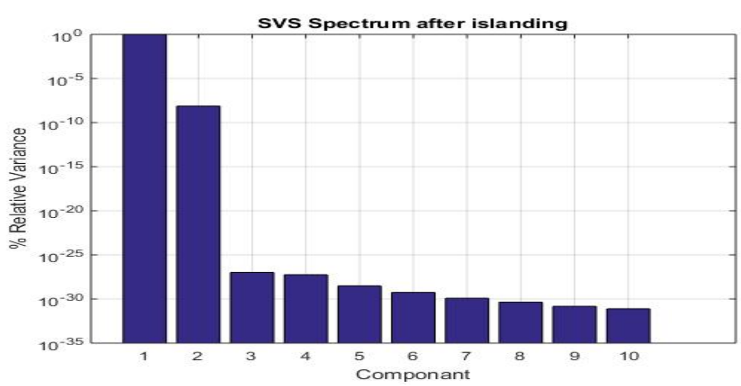
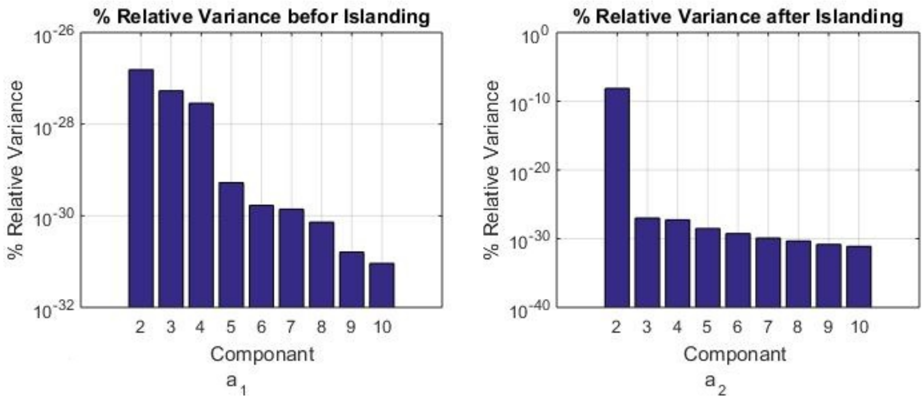
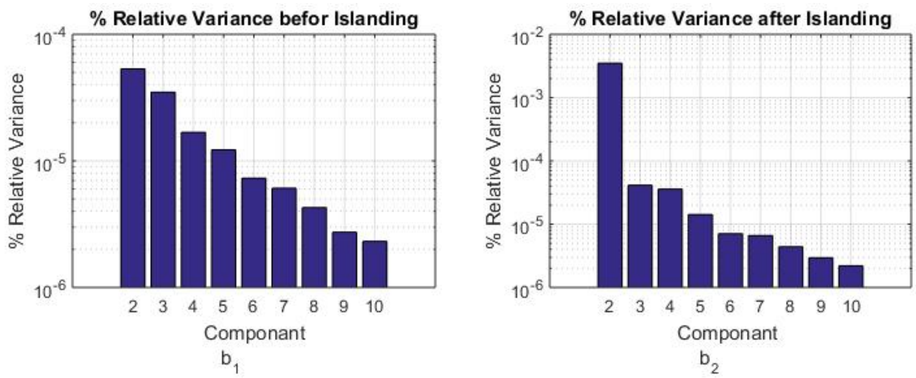


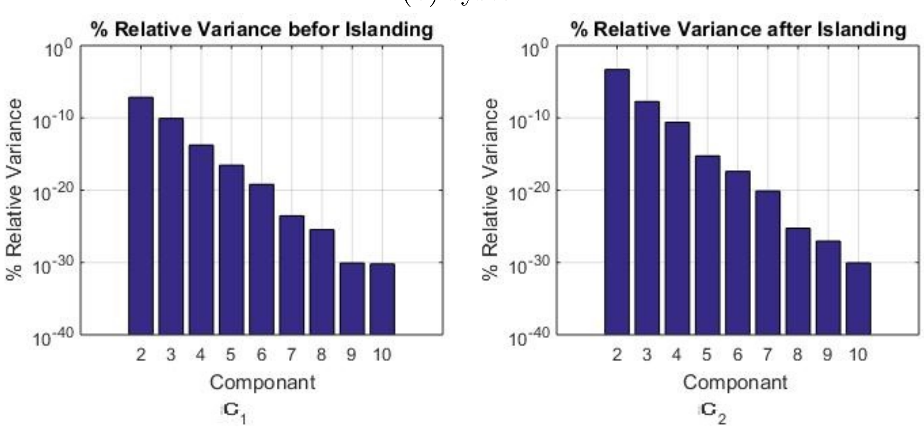
Figure 4.3: The relative variances for system 1 in islanding scenario.



(a) system 1



(b) system 2



(c) system 3

Figure 4.4: The relative variances

islanding conditions. These are in addition to the two scenarios in which a large capacitor (rated one p.u.) is switched in the grid, as well as the starting of a large induction motor (rated one p.u). First, each scenario is simulated separately for 5 seconds (300 cycles). The voltage was calculated and sampled using 1000 samples for each cycle. At cycle 120 (in the 2nd scenario), disturbance was imposed for all scenarios in which an abnormal activity is required. After calculating the voltage, matrix X was constructed from cycle 111 to 120 to include the first cycle at which islanding occurred, as defined in section 2.2 The 2nd to the 6th singular values were calculated and fed into the ANN for training. A new voltage matrix was formed from cycle 112 to 121, and singular values from 2 to 6 were calculated once more and fed into the ANN for new training. Proceeding in the same manner through cycles 113 to 122, 114 to 123,....,120 to 129 . It can be noted that cycle 120 is repeated for all of the calculated voltage matrices, which was intentional. Taking cycles following 120 to 129 will lead to false training and false results due to the assumption that systems regain normal operation after one cycle, which is valid in some cases.

4.4 Testing the proposed algorithm

Voltage profiles under different scenarios, as shown in Table 4.1 were generated for the purpose of testing the ANN. Each scenario was simulated for 300 cycles. During simulation the first ten cycles construct the first voltage matrix. The second to sixth singular values of the voltage matrix are fed into the ANN for training.

Table 4.1: scenarios for testing the proposed technique.

scenario 1	10 % increase of load
scenario 2	10 % decrease of load
scenario 3	110% pu rated capacitor switching
scenario 4	110% pu rated induction motor IM starting
scenario 5	Disconnect the Bio-mass DG

After tabulating the results of the ANN, the new singular values, calculated from the second voltage matrix which consist of the cycles from 2 to 11, are fed into the ANN for testing. The previous process is then repeated until all the cycles are accounted for. The results are discussed below.

Scenario I: 10 % increase of load

In the first scenario, the active power mismatch between the generation of power and the load is increased 10% by increasing the load. Table 4.2 shows the result of the output of the ANN. The output of the ANN is greater than one half at cycle 120 which indicates islanding. The islanding occurred after 2 seconds which means that it started at cycle 120. For the three systems it took 16.7 ms (one cycles) to detect islanding using the SVD method.

Table 4.2: The output of the NNT for the first scenario.

Cycle number	System 1	System 2	System 3
116	-0.001	-0.0108	1.69×10^{-5}
117	-0.001	0.00057	1.69×10^{-5}
118	-0.001	-0.0178	1.69×10^{-5}
119	-0.001	0.00384	1.695×10^{-5}
120	**0.69170**	**1.00**	**1.153**
121	0.8732	0.8314	1.00
122	1.0135	0.8909	1.00
123	1.003	0.9606	1.00

Scenario II: 10 % decrease of load

In this scenario, the active power mismatch between the generation of power and the load is decreased 10% by decreasing the load. Islanding was detected after the first cycle. The output of the ANN is shown in Table 4.3.

Table 4.3: The output of the NNT for the second scenario.

Cycle number	System 1	System 2	System 3
116	-0.0012	-0.0415	1.689×10^{-5}
117	-0.0012	-0.0513	1.689×10^{-5}
118	-0.0012	-0.0346	1.689×10^{-5}
119	-0.0012	-0.021	1.689×10^{-5}
120	**0.5069**	**1.010**	**1.153**
121	2.329	0.6289	1.0033
122	1.164	0.9149	1.0068
123	1.009	0.983	1.06293

Scenario III: 110% pu rated capacitor switching

In all three systems, a capacitor rated 1.2 pu was switched on the grid to identify its effect on islanding algorithm. Figure 4.5 shows the effect of the islanding on the secondary components. Although the capacitor switching caused an increase in the relative variances of the secondary values, the severity of its effect is lower than the effect of islanding. As a result, ANN was able to distinguish capacitor switching from islanding. Table 4.4 shows the output of the NNT. Figure 4.6 shows the voltage at PPC when the capacitor was switched

Table 4.4: The output of the NNT for the 3rd scenario.

Cycle number	System 1	System 2	System 3
116	-0.0012	-0.0323	1.689x10^{-5}
117	-0.0012	-0.0226	1.689x10^{-5}
118	-0.0012	-0.0167	1.689x10^{-5}
119	-0.0012	-0.0072	1.689x10^{-5}
120	0.0122	0.3059	-3.313x10^{-5}
121	0.1978	0.1871	1.689x10^{-5}
122	-0.0995	0.15502	0.010334
123	0.0237	-0.0056	0.068131

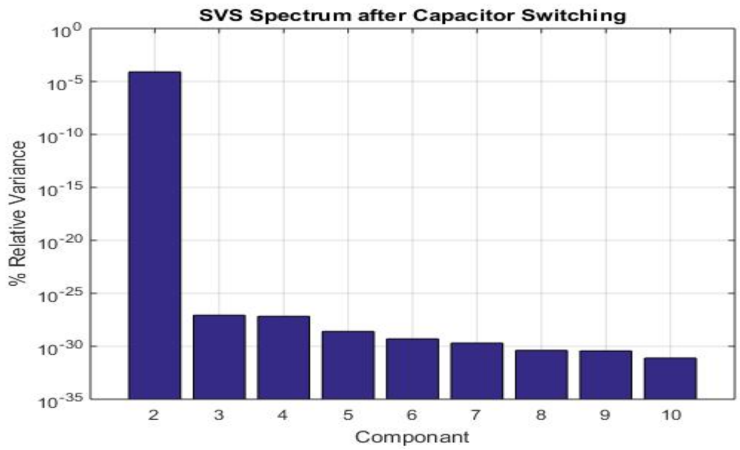
Table 4.5: The output of the NNT for the 4th scenario

Cycle number	System 1	System 2	System 3
116	-0.0012	-0.0205	1.689x10^{-5}
117	-0.0012	-0.0532	1.689x10^{-5}
118	-0.0012	-0.0502	1.689x10^{-5}
119	-0.0012	-0.0535	1.689x10^{-5}
120	0.0194	0.2877	1.667x10^{-5}
121	0.0926	0.2262	1.671x10^{-5}
122	0.1180	0.1567	1.679x10^{-5}
123	0.1323	-0.0045	1.679x10^{-5}

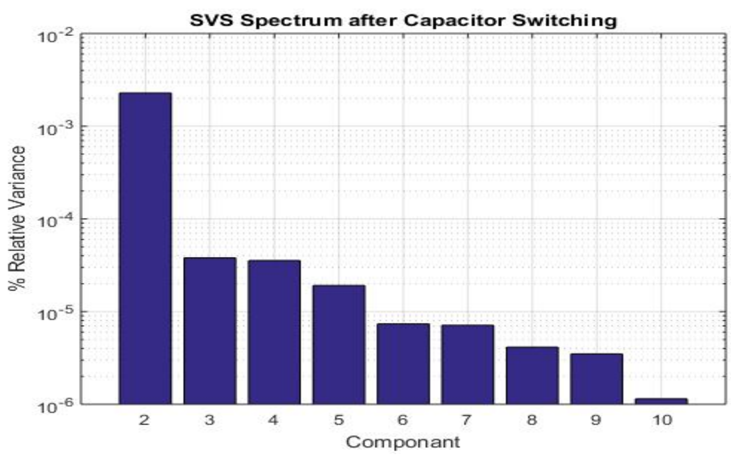
after 2 seconds.

Scenario IV: 110 % pu rated induction motor IM starting

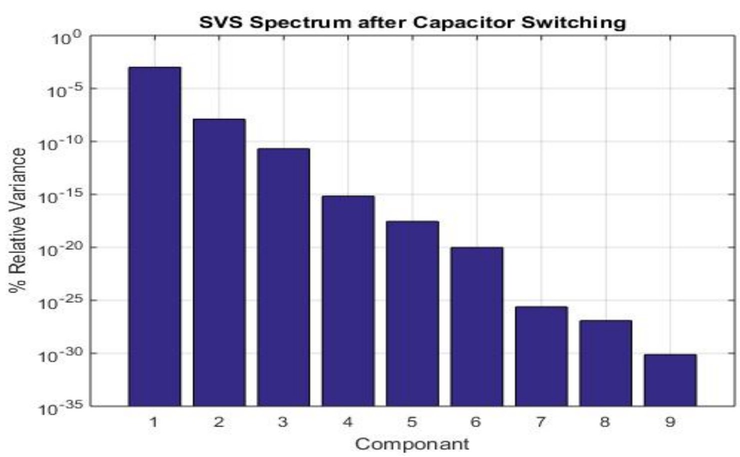
In all three systems an induction motor rated 1.2 pu was switched on the grid to identify its effect on the islanding algorithm. The effect of a motor starting is shown in Figure 4.7. Although the secondary values are affected by the motor starting, ANN can still distinguish islanding in this case. Table 4.5 shows the output of the ANN.



(a) system 1

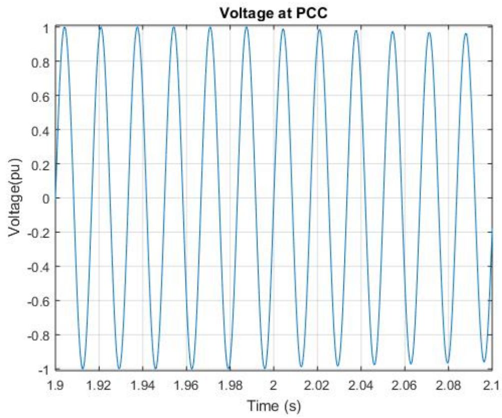


(b) system 2

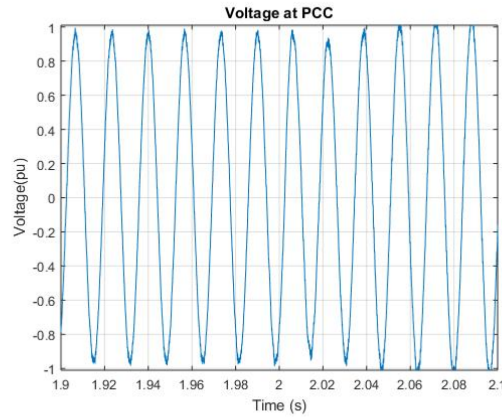


(c) system 3

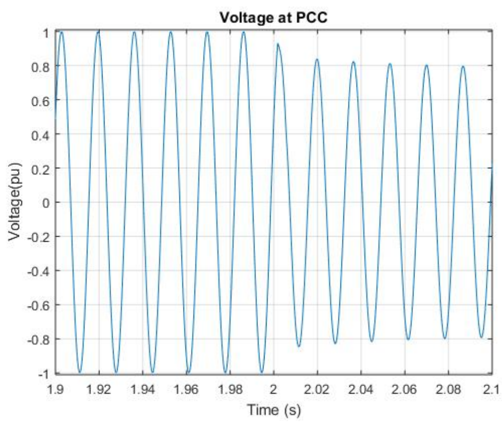
Figure 4.5: The relative variances in case of Capacitor switching.



(a) system 1



(b) system 2

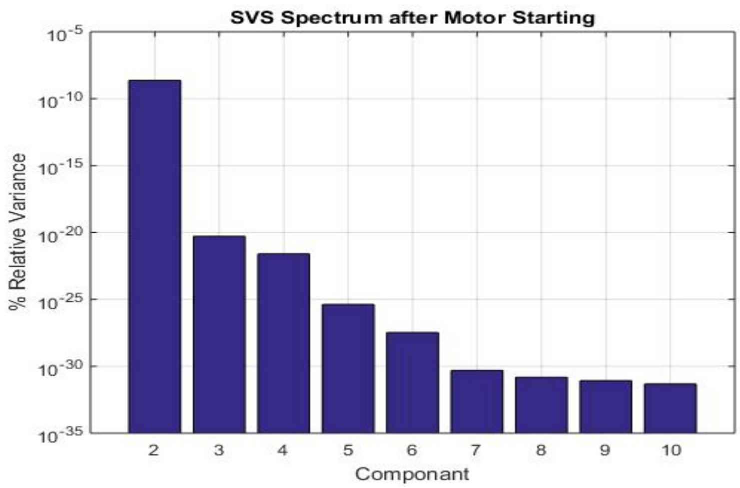


(c) system 3

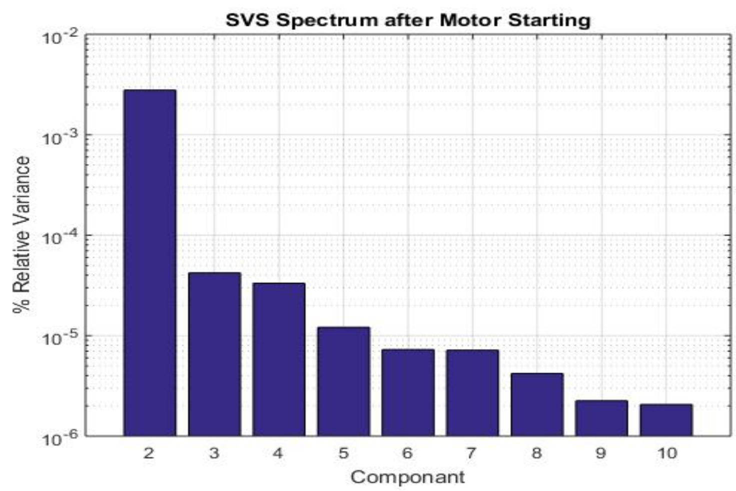
Figure 4.6: The Voltage in for scenario III.

Scenario V: Disconnect the Bio-mass DG

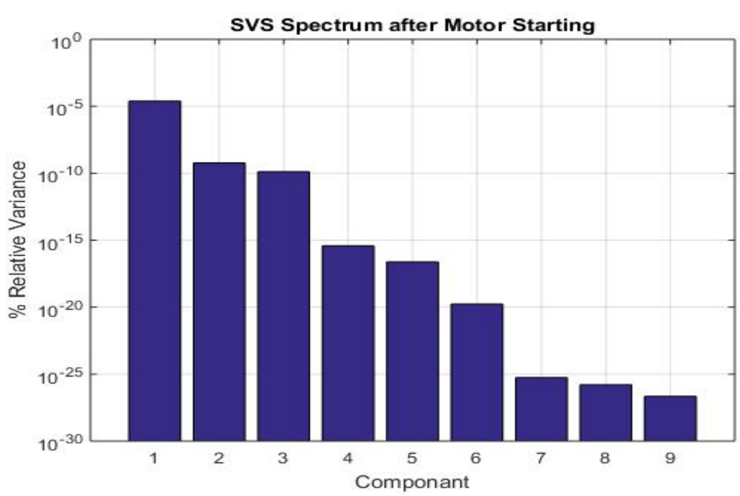
It is vital to test any technique against false detection. Furthermore, in hybrid system the disconnection of one of the generators may lead to false detection. In system one, there is a scenario in which the bio mass generator was



(a) system 1



(b) system 2



(c) system 3

Figure 4.7: The relative variances for motor starting.

Table 4.6: The output of the NNT for the 5th scenario.

Cycle number	117	118	119	120	121	122	123
System 3	1.689x10^{-5}	1.689x10^{-5}	1.689x10^{-5}	1.687x10^{-5}	1.687x10^{-5}	1.687x10^{-5}	1.687x10^{-5}

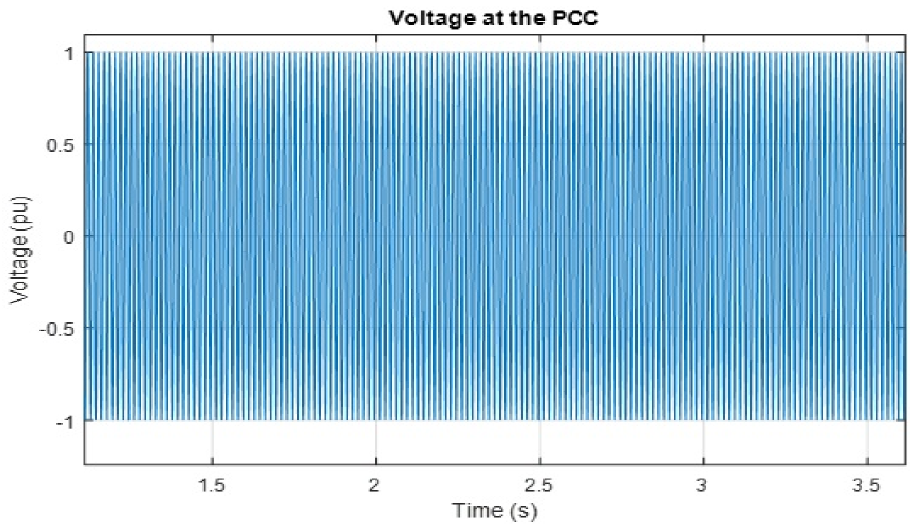


Figure 4.8: The Voltage for scenario V.

disconnected by opening the circuit breaker. There was no indication of islanding, which means that the proposed method is operating well. Table 4.6 shows the output of the ANN. Figure 4.8 shows the voltage at PPC. The Bio-mass unit is disconnected after 2 seconds.

4.5 Additional scenarios

In the prescribed islanding detection algorithm, we conducted testing with abnormal operations. The method showed robustness in detecting and separating islanding from disturbances; however, the power distribution system is considered chaotic, and if changed, it is not easy to consider all scenarios in the testing of the method. Also, the method uses NN to classify islanding, which is a flexible tool; that is, additional scenarios can always be included by training the NN for efficient detection.

In this section, a number of possible scenarios which can lead to a false detection and/or be overlooked are considered for testing without retraining the NN to test the validity of the method. Situations such as adding DG to the system and loading the DG with loads equal to generation are considered as misleading cases for the algorithm.

System 3 used to experiment with two scenarios one is generation equal to the load, the other was done by adding another Bio-mass station, rated 2 MVAR in cycle 120. The method was used to test the output of the NN, as shown in Table 4.7. It can be clearly noticed from Table 4.7 that the method was able to differentiate between islanding and the addition of another DG in the system. Also, the method was able to detect islanding when the generation was equal to the load, as shown in the table.

For small distribution transformers up to 1000 kVA, which are installed in distribution substations in urban areas, the level of allowed noise is limited to 64 dB. Regarding permitted noise levels, most national standards and European countries have stricter requirements than international standards, which prescribe the approximate values for transformer manufacturers. For example, the require-

Table 4.7: The output of the NNT for the nominal loading and adding another DG

Cycle number	Generation equals load	Adding a DG
116	2.05×10^{-6}	2.05×10^{-6}
117	-1.101×10^{-5}	2.05×10^{-6}
118	-1.57×10^{-5}	2.05×10^{-6}
119	-6.59×10^{-6}	2.05×10^{-6}
120	**1.0**	**2.05x**10^{-6}
121	1.0	2.05×10^{-6}
122	1.0	2.05×10^{-6}
123	1.0	2.05×10^{-6}

ments of the German, Austrian and Czech power generation industry, in which the permissible noise of the distribution transformers of power 50 kVA is 42 dB, and the permissible noise of the distribution power transformers of power 1000 kVA is 48 dB [75]. Multiple noise levels were applied to the voltage signal for system 2 to test the methods robustness. Table 4.8 shows the output of the NN. From this table, the method was able to detect islanding in the case of high noise levels. However, when noise levels increase above the permissible level, the detection of islanding becomes delayed. An example of this case is the 40 dB noise level with islanding occurring at cycle 120. In this case, the method detects islanding without retraining the NN in cycle 121 (second cycle); however, 42 dB is the permissible level of noise in most standards [75].

Table 4.8: The output of the NN after adding noise

Cycle number	64 dB	42 dB	40 dB
116	-0.0125	-0.144	-0.223
117	-0.001	-0.144	-0.2302
118	-0.020	-0.158	-0.225
119	0.003	-0.146	-0.215
120	**0.690**	**0.661**	0.4445
121	0.8298	0.829	**0.6185**
122	0.890	0.947	0.839
123	0.960	0.947	0.9448

CHAPTER 5

CONCLUSION

In this work, a new islanding detection method is proposed using SVD and PCA tools. The results show that islanding is detected in less than two cycles (about 17 ms). Unlike the majority of signal processing techniques, the proposed detection method works on many typologies. This is due to the advantages of component analysis on voltage signals. Studying the principle components of a voltage signal disturbance caused by islanding, such as phase shift, voltage sag/swell, and harmonics distortion, shows that these components will all affect the voltage signal component, thus making islanding easy to identify. The use of ANN as an intelligent classifier, instead of the traditional threshold setting, makes it much easier to distinguish islanding from other disturbances. Also, the technique separates noise from disturbances, which thus makes it more immune to noise.

5.1 Summary of Contributions

1. Development of a novel solution for islanding detection of distributed generators using PCA and SVD analysis tools.

   This thesis presents a new concept of islanding detection based on the concept of PCA using singular values analysis. The change in singular values between island- and utility-connected systems is the threshold trigger. The proposed concept provides a more effective signal processing based islanding detection scheme that can be used with naturally occurring unbalanced loads.

   The advantages of signal processing-based islanding detection include the wide range of applicable configurations, minimal integration costs, accuracy using naturally occurring unbalanced loads, and a fast response time of 16.7 ms compared to the 2 s IEEE 1547 standard. The minimal integration costs are a result of only requiring an existing VT system without having to install expensive and highly sensitive equipment to access voltage. In the systems under study, the proposed method provides a zero NDZ with the ability to adapt to numerous disturbances.

2. Theoretical analysis and performance of voltage measurement for islanding detection.

   The concept of principle component analysis for islanding detection has been proven algebraically and through various simulations. The proof identified the correlation of singular values to the islanding condition. This thesis models how each component is created, and demonstrates the method performance characteristics in terms of load sizes, type of generator used, connecting utility strength, and the effects of multiple loads. The advantage of this analysis is that the performance characteristics are clearly expressed and can be used to further determine the suitability of the method in a number of scenarios.

3. Disturbance Performance and ANN implementation.

   It has been found that using singular value analysis is preferable and more immune to noise over other signal processing techniques, as disturbances create errors that may lead to undesired tripping. The use of singular values has been proven that it can separate islanding from other disturbances. For example, if a DG shuts down or if a capacitor is switched in the network.

   The use of ANN increases the system reliability and solves the problem of threshold calibration. The use of traditional threshold calibration is considered a difficult task, especially when considering other disturbances such as those considered in this study. ANN provides a solution for this problem and also improves the method by concentrating on the way that islanding affects singular values rather than the amount.

4. The validity of implementing the proposed method on a number of different architectures of distribution networks.

   Many signal processing and or other islanding detection techniques are defined as a single DG design in which the system has a rotating or an Inverter-based DG. In the aforementioned islanding detection method, the same procedure is applied to an inverter and a rotating machine-based DG. The method was deemed successful in both tests .

5.2 Future Work

The SVD based islanding detection technique has been demonstrated to operate in many ideal network conditions; however, there are several significant areas to be explored in this work:

1. The implementation of the proposed method on real live loads.

   Although the simulation provides to a certain extent, it is hard to detect the behavior of the system in real life. It is preferable to implement the proposed method on a distribution grid, and it also acts as a way of studying the method's robustness under abnormal conditions, including a variety of system configurations.

2. The use of the method to implement a solution for unbalanced loads in case of islanding.

   In [76], the authors suggested a new method for load shedding in case of islanding. This method is considered very effective, especially in the case of critical loads in which, even though the connection to the grid is severed, the DG is allowed to continue to supply power to local loads. This technique provides the means necessary to detect such a disconnection in a very short time-span. Also, this technique can be central to maintaining system stability during islanding with some modification.

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